ANNUAL REPORT 2019

NCCS
NORWEGIAN CCS RESEARCH CENTRE

NCCS

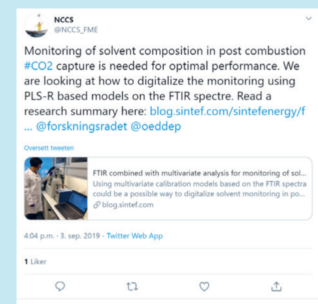
CO_2 capture, transport, and storage (CCS) is a process where waste carbon dioxide (CO_2) is captured from large industrial plants, transported in pipelines or ships and deposited (e.g. in an underground geological formation) so it will not enter the atmosphere. EU energy and climate targets cannot be met costeffectively without CCS, while making sure we have enough energy to go around.

NCCS aims to fast-track CCS deployment by working closely with industry on research topics designed to address major barriers to making CCS happen in Norway, Europe, and the world.

NCCS (Norwegian CCS Research Centre) is a Centre for Environment-friendly Energy Research (FME).

Selected highlights from 2019

@NCCS_FME



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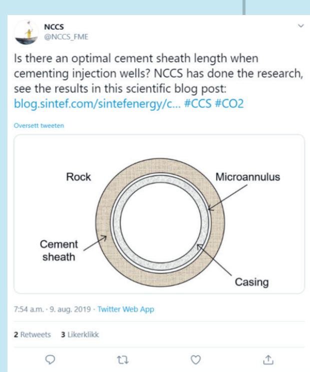
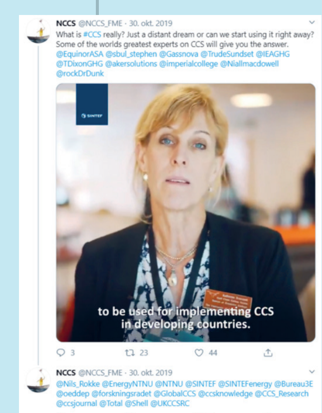




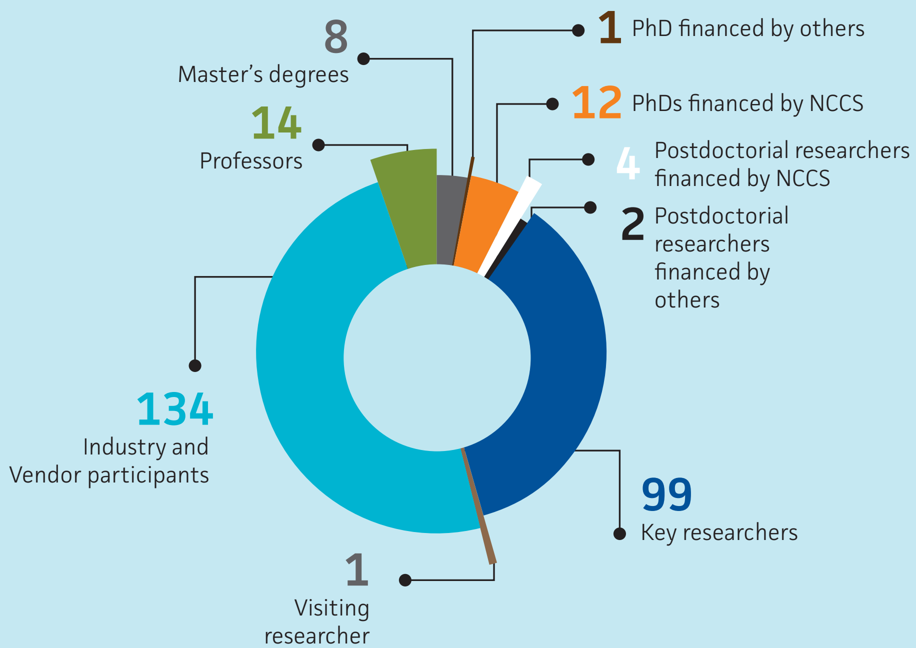
2019 BY NUMBERS

28 PARTNERS

8 YEARS

465 MNOK

People



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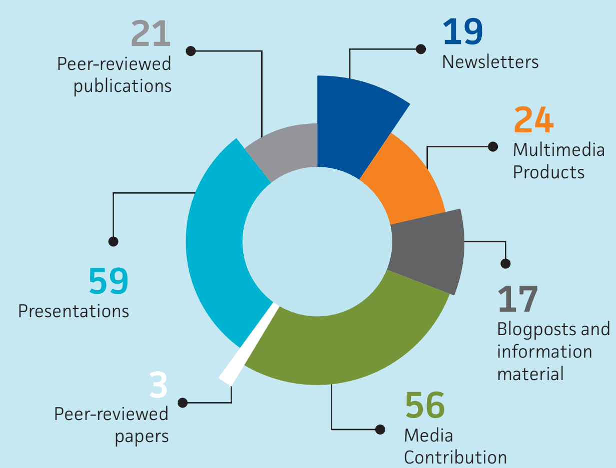
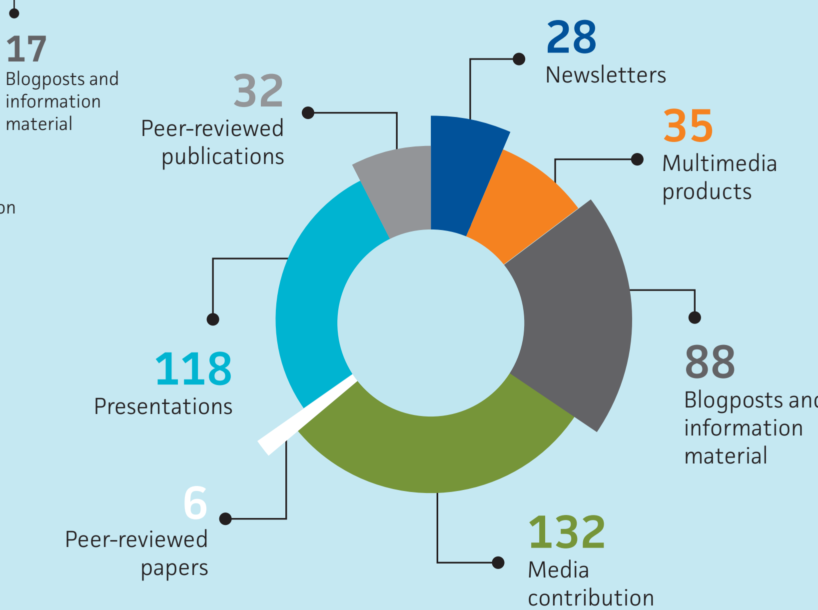
Communication and dissemination 2019



Communication and dissemination 2016-2019



There might be some discrepancies between the numbers in the figure and numbers registered in Cristin, mainly due to FME partners that do not have a university or research institute affiliation or because the FME project code has not yet been registered in the post.

Lower CCS cost and risk through better CO_2 viscosity and thermal conductivity

Viscosity is a property that is important for several CCS processes. In lay-man terms, viscosity can be expressed as the resistance of a fluid to flow. To illustrate the concept of viscosity, an example that should be familiar to all is syrup, which at room temperature does not flow easily and hence has a relative high viscosity. If heated up, however, syrup flows much easier and hence has a lower viscosity. Viscosity is included in models for flow and heat transfer. The property is particularly important whenever the flow can be said to be laminar, i.e. when the flow is free from turbulence.

Find out more: **www.nccs.no** – Annual report 2019

Utilization of municipal solid waste to achieve negative CO_2 emissions

The Calcium Looping process represents one option for post-combustion CO_2 capture from conventional power or industrial plants. In this process, a limestone-based sorbent stream circulates between two interconnected circulating fluidized bed (CFB) reactors. The CO_2 is separated due to cyclic carbonation and calcination of the circulating sorbent. The process can also be applied to the waste-to-energy sector. Municipal solid waste (MSW) allows for negative CO_2 emissions due to its large organic waste fractions. Negative CO_2 emissions are required to limit anthropogenic climate change effects.

Find out more: **www.nccs.no** – Annual report 2019

FAST-TRACKING CCS DEPLOYMENT IN NORWAY, EUROPE AND THE WORLD

Europe is steering towards a net zero-CO_2 emission economy. "To make that possible, we need to maintain a high level of security of supply, low cost of energy while at the same time maintaining the very crucial process-industries in Europe. But industrial companies have to operate very differently in 2050 than today if we are to reach our climate targets. It is very hard to see this happening without a huge deployment of CCS across Europe", says Tord Lien, NCCS Chairman of the Board.

"That's why a research centre like NCCS, where industry, R&D, authorities and academia cooperate to fast-track CCS deployment in Norway, Europe and the world, is so important".

Mona J. Mølnvik

Dr. Mona J. Mølnvik is the NCCS Centre Director.

She has been with SINTEF for 20 years, and has been active in CCS research since the early 2000s. Mona holds a PhD within mechanical engineering from NTNU and is Research Director for the Gas Technology department at SINTEF Energy Research.

She was central in developing and leading the centre of excellence, FME BIGCCS – International CCS Research Centre (2009-2016). Further, she has been involved in several EU-projects. Mona has been a central contributor to development of CCS research strategies, and she was the first leader of the CO_2 transport initiative under EERA JP Carbon Capture and Storage.

Tord Lien

Tord Lien is the NCCS Chairman of the Board and Regional Director for Trøndelag at The Confederation of Norwegian Enterprise (NHO).

Before joining NHO in 2017, Lien was Minister for Petroleum and Energy (2013-2016). As Minister, Lien played a central role in developing and transitioning the Norwegian energy-, oil- and gas sector in a challenging economic period in Norway.

He represented The Progress Party in parliament (2005-2013) and has a Master's degree in history from NTNU (1999 – 2003).

2019 – a year of great importance for NCCS research and strategy

"2019 was a great year for NCCS! We have produced strong scientific results, which you can read more about in this report. The involvement from industry is stronger than ever. We have a great team of industry experts (vendors and users) and a team of research partners, both national and international, with high engagement in the Centre. Because of international collaborations, there have also been several spin-off projects from NCCS in the EU H2020-programme", says Mona Mølnvik, Director of NCCS.

The year kicked off with the presentation of *the Effect Study* to the (then) Minister of Petroleum and Energy, Kjell-Børge Freiberg. The study showed that energy research leads to important, profitable innovations for industry. "In this study, we have explained the specific value of our research", Mølnvik says.

Two new industry partners joined the Centre in 2019: Lundin AS and Vår Energi. Also, Baker Hughes are in the final stages of joining NCCS. "We are extremely proud to have them on board. It's a huge achievement for us. Without industry support, there would be no research. We cannot stress the importance of our close cooperation with industry enough", says Mølnvik.

NCCS' already strong coupling with a broad industry continued in 2019 as Tord Lien was introduced as the new Chairman of the Board. Lien is a Regional Leader in the The Confederation of Norwegian Enterprise (NHO). He is also a former Minister of Petroleum and Energy in Norway.

"Tord will work with NCCS on a strategic level by connecting and working more closely with industry, in addition to promoting CCS even more in Norway, Europe and other parts of the world", explains Mølnvik.

Five new spin-off projects started up last year. Among these are competence building projects with funding from the CLIMIT, PETROMAKS and Energi X programs operated under the Research Council of Norway. Together with the two spin-off projects in 2018, they have given the Centre an extra 60 million NOK in funding. "This is a huge achievement and it brings more momentum into the Centre" Mølnvik says proudly. "An example of another industry-anchored spin-off

project is the CLIMIT Demo-funded Preem project", Mølnvik says. The main objective is for Preem to undertake on-site CO_2 capture from their hydrogen production facility at Lysekil. The goal is to enable full-scale CO_2 capture with connections to the Norwegian Full-scale Project.

"In June, we hosted the 10th Trondheim CCS Conference (TCCS). TCCS is the world's second largest scientific CCS conference with more than 400 delegates from all around the world, representing industries, governments, research institutes and NGOs", Mølnvik explains.

Norway as a frontrunner on CCS – Possibilities, climate contribution and value creation in industry

Countries have a moral obligation to help achieve the Sustainable Development Goals and the Paris Agreement. Because of Norway's ability to store CO_2 on our Continetal Shelf, CCS can be one of our big contributions to reaching these goals", Lien says.

He also emphasizes that there are economic benefits to a Norwegian CCS industry. "There is an obvious change in the European energy market. We see a strengthened demand for hydrogen. At the same time, Norway has high levels of natural gas remaining on the Continental Shelf. If we make hydrogen from natural gas, use CCS to capture the CO_2, deposit it back on the Norwegian Shelf and sell hydrogen to Europe, we will help Europe become the first continent with net zero emissions, while at the same time creating jobs and income for Norway", he says.

In 2020, the Norwegian Government will decide whether to invest in a CCS infrastructure, enabling large-scale

CCS deployment. "This is one of the most important decisions that needs to be made in Norway next year" Lien says.

"This is also highly motivational for researchers that have been working on this project for many years, to actually witness the results of what they have been working on and to be realized on a huge scale", says the Chairman.

A typical counterargument for investing in CCS is costs. But Mona does not see cost as a barrier. "First of all, implementing full-scale CCS in Norway, Europe and other parts of the world will in itself bring costs down. The overall competence and knowledge in the field will also increase. Together with continued research effort, this will lead to innovations in addition to bring incremental changes within existing technologies. Both will bring costs down", says Mølnvik. She mentions the Boundary Dam CCS Project in Canada. They have already built one CO_2 capture plant and are looking at a 67% cost-reduction* for CO_2 capture in their next plant. "There is no reason for not having many more full-scale CCS projects around the world" Lien adds.

*https://ccsknowledge.com/news/cost-of-capturing-co2-drops-67-for-next-carbon-capture-plant

NCCS IN A NUTSHELL

NCCS aims to fast-track CCS by working closely with the industry on research topics designed to address major barriers in making CCS happen in Norway, Europe, and the world. NCCS research focuses on two "CCS Deployment Cases": *CCS for Norwegian Industry* and *Storing Europe's CO_2 in the North Sea*.

Fast-tracking CCS is a joint effort. NCCS is a collaborative project between 28 partners in industry, research institutes and other organisations, in 10 countries and om three continents. NCCS also has 7 associated partners. NCCS is led by SINTEF Energy Research in Trondheim, Norway.

As an industry-driven Centre, our industry partners guide and prioritize the research tasks to tackle industrial challenges related to CCS. Each task has a "family" with members who are actively engaged and contribute to the development of the work plans and in the research activities. Research in NCCS is organised in 12 tasks covering the whole CCS chain. The tasks address critical challenges for realizing CCS for Norwegian industry and storing Europe's CO_2 in the North Sea. In addition, efforts have been made to ensure dialogue with the Norwegian Full-scale Project.

NCCS Annual Consortium Days

NCCS held its annual Consortium Days on October 22 and 23 in Trondheim with more than 80 delegates representing all the consortium partners. The event was organised with plenary sessions on day one and three break-out parallel sessions on day two. On day one, the focus was on "highlights and the latest research results" and presentations of the new spin-off projects, while the break-out sessions on day two focused on innovations and potential for value creation. The NCCS Board also had its 8th meeting on October 23.

Centre Director Mona Mølnvik on stage during the NCCS Consortium Days 2019.

New Partners in 2019

All NCCS partners continue to make important contributions to our research. Thank you to all!

In 2019, we were proud to introduce two new partners to NCCS: Vår Energi and Lundin AS. Baker Hughes is also in the final stags of becoming a partner, and will officially be part of NCCS in 2020. Moving into 2020 we continue to look for new partners to join our mission to fast-track CCS deployment through industry-driven science-based innovation.

Vår Energi
Vår Energi joined the NCCS partnership at the beginning of 2019 with an agreement worth NOK 30 million over six years.

Vår Energi AS is a new, leading, independent E&P company on the Norwegian Continental Shelf (NCS) and the result of the merger of Point Resources AS and Eni Norge AS in late 2018. Vår Energi is jointly owned by the Italy-based energy company Eni (69.9%) and the Norway-based leading private equity investor HitecVision (30.4%). Every year, Vår Energi invests over NOK 100 million in R&D projects on the NCS.

"This partnership complements Vår Energi's research and development portfolio. The company is committed to reduce the emissions of greenhouse gases through CCS technology development.

Our objective is to further minimize environmental impact in our operations, and reducing greenhouse gas emissions is a key element in our mission. The Vår Energi-operated Goliat field in the Barents Sea demonstrates this commitment by being mainly electrified with power from shore, making it one of the lowest CO_2 emitting fields on the Norwegian Continental Shelf. All initiatives to reduce the carbon footprint are positive, and CCS deployment is an effective measure. We hope that our contribution in addition to others, will further enable NCCS' progress"

- Oddvar Ims, R&D Manager in Vår Energi.

Lundin AS
Lundin AS joined NCCS at the end of 2019 with a contribution of NOK 30 million. A main area of focus for Lundin in 2019 has been to identify measures to reduce emissions in its entire value chain.[1]

Lundin Petroleum was founded in 2001 and entered the Norwegian Continental Shelf in 2003. Since then the company has grown to become one of the largest operated acreage holders in Norway with a strong production growth profile for coming years.

Each year, Lundin spends more than NOK 100 million on research and development projects. Lundin's highly-skilled experts cooperate with research institutions, universities and other commercial players.

An important key to success in this type of collaboration is their policy of not owning patents or rights to products or technologies. They want to be good at using technology, not selling it. Joining NCCS is a part of that strategy.

[1] Lundin Petroleum Sustainability Report 2019

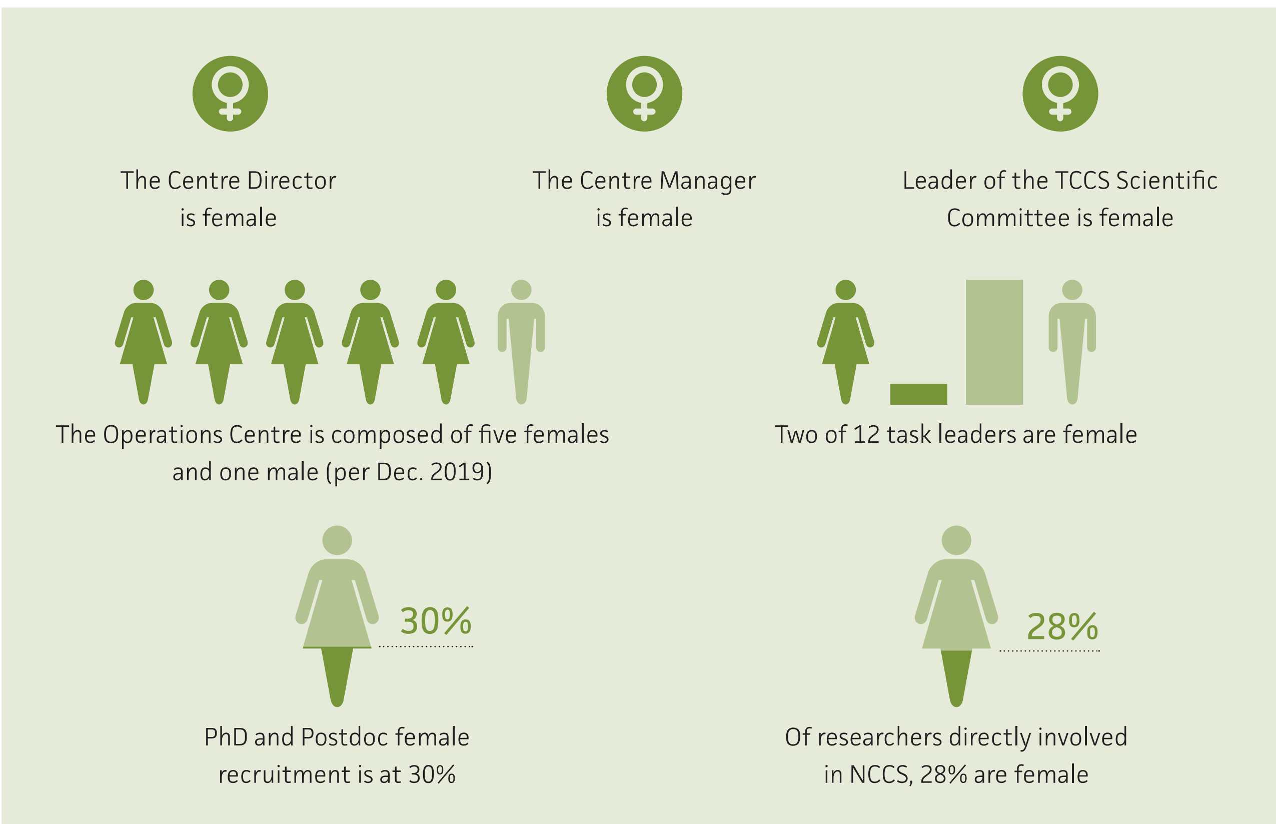
Baker Hughes
Fiscal metering is an enabler for CCS to allow for avoidance of Emission Unit Allowances (EUAs) purchase in CCS where EU emission trading system (ETS) requires traceable metering. Baker Hughes is a leading supplier of ultrasonic fiscal meters (Panametrics line), which they claim are suitable for CCS conditions. Baker Hughes will join Task 8: Fiscal Metering and Thermodynamics, where they will provide a fiscal meter for static testing and assist in running these tests. Baker Hughes will provide industry knowhow on state-of-the-art ultrasonic flow meter technology and provide input and guidance in the design and development of a fiscal metering test loop.

Gender balance

NCCS aims for equal opportunities and gender balance at all levels of the Centre's organisation, and encourages all partners to collectively achieve the EU target of recruiting at least 40% female staff in scientific positions. The academic partners encourage female applicants through open announcements, thus striving for gender balance when employing PhD candidates and Postdocs.

Central issues for the Operations Centre during 2020:

- NCCS wants to take on a more active role in the recruitment of younger women to the field of CCS. Participating at student recruitment campaigns at NTNU is a prioritized activity.
- NCCS wants to increase the visibility of female researchers at the NCCS Consortium Days. From 2020 the portion of female speakers will be at least 40%.
- NCCS wants to increase the female portion of NCCS task leaders. Women will be chosen for new positions, other qualifications being equal.



VISION AND GOALS

NCCS will enable fast-track CCS deployment through industry-driven science-based innovation, addressing the major barriers identified within demonstration and industry projects, aiming at becoming a world-leading CCS centre.

NCCS aims to be a world-class national and international multi-disciplinary CCS partnership between operators, vendors and academia that have united to address one of the greatest challenges of our time: climate change. Capacity is built to capture, transport and store billions of tons of CO_2 by fast-tracking CCS deployment. NCCS is a dynamic, forward-looking approach that will maximize new and current knowledge to make CCS happen – in time to meet EU climate targets. CCS in the North Sea Basin has the potential of becoming a NOK 50,000 billion profitable business.

Goals

The overall objective is to fast-track CCS deployment through industry-driven science-based innovation, addressing the major barriers identified within demonstration and industry projects, aiming at becoming a world-leading CCS centre.

NCCS supports and aligns with the Norwegian Full-scale CCS Project to realize the Government's ambition to have this operational in 2020. This includes addressing technical and legal barriers via targeted research covering the full CCS chain.

NCCS develops science-based strategies for large-scale CO_2 storage and is a key facilitator for storage in the Norwegian North Sea Basin. This includes aligning with European CCS projects, while addressing technical and legal barriers via research on the full CCS chain.

Scientific objective

Provide a frontier knowledge base for the technology breakthroughs required to fast-track full-scale CCS, with industrial relevance, by use of decision gates and priorities of the NCCS industry partners.

Innovation objective

- Fulfill the commercial ambitions and needs of industry and society, while maximizing innovation in deployment cases.
- Establish a targeted spin-off programme for the execution phase of innovation processes and their faster adoption.
- Establish new research projects within topics where knowledge gaps are identified.
- As part of the innovation process, design a comprehensive IP strategy.

Recruitment objective

Recruit and educate young people (24 PhDs, 5 Post-docs, 80 MSc graduates), reflecting gender balance and equal opportunities, with first-class competence in CCS-related topics to ensure recruitment to both industry and research institutions.

International objective

- To be a CCS research hub benefitting from close cooperation between highly ranked academic institutions in Europe and North America.
- Influence Europe's CCS strategies by participating in the development of the SET Plan, the Integrated Roadmap for CCS and working programs in Horizon 2020 as members of the ZEP Technology Platform and the European Energy Research Alliance (EERA) on CCS.
- Support and strengthen the memorandum of understanding (MoU) between the US DOE and the Norwegian Ministry of Petroleum and Energy on CCS research by offering to operate a secretariat for the MoU initiative.

SAILING TOWARDS LOWER COST & LEGAL CERTAINTY FOR CCS

When the idea of large-scale CCS was introduced, pipelines were foreseen as the main means of transport due to the low cost for large capacities. But with a stronger focus on bringing European CO_2 emissions to the Norwegian Continental Shelf, shipping has now emerged as a more attractive option from both a cost and risk perspective.

Sailing towards lower cost & legal certainty for CCS

Simon Roussanaly, Research Scientist at SINTEF Energy Research

Catherine Banet, Associate Professor - Scandinavian Institute of Maritime Law

Bringing CO_2 capture, transport and storage (CCS) technologies to commercialisation is a necessary step to reduce emissions as we grapple with meeting the Paris Agreement commitments. Yet a frequent media comment is that CCS is too expensive to become a viable commercial option at scale. NCCS research has focused on further reducing the cost of CO_2 shipping, but also revealed the need for significant legal work to untangle uncertainties over liabilities.

Identifying optimal shipping conditions to reduce cost

CCS cost reduction typically focuses on the capture process, but conditioning and transport costs can also be significant especially for start-up deployments. One specific example of cost-cutting research has centred around optimal transport temperature and pressure conditions for CO_2 by ship. While the pressure range beyond 20 bar has been identified as not cost-efficient, no study has satisfactorily concluded on the optimal transport condition.

NCCS examined a question often asked by industry: whether the 7 bar shipping option could be more cost-efficient than the 15 bar option currently used in commercial shipping. The answer is yes!

Results so far show that the 7 bar option can enable significant cost reduction in most scenarios. Typically, costs for conditioning and transport can drop by 15%, while costs for transport distances beyond 1,000 km can drop by 30% or more. "However, more research and development is required to enable the 7 bar technology at scale. At present, the 15 bar technology remains the only mature and low-risk option for short-term implementations such as in the Northern Light Initiative," explains Simon Roussanaly, leader of NCCS Task 1.

Understanding uncertainties and legal bottlenecks

But the work on shipping doesn't end by bringing down the cost. It's also important to identify and reduce legal uncertainties and barriers in order to enable the commercial implementation of CO_2 transport by ship.

Critical legal topics such as liability must be understood and have a sound legal basis if operators

and governments are to buy into shipping as an option. Simply put, a strong legal framework that lays out liability for any leakage or other issue that may occur along the chain and also during a cross-border transportation must be in place, and it must be watertight. Developing adequate legal instruments (by law, contracts or financial support to activities) that can be used to mitigate risks and enable various transport solutions is a key task within NCCS.

Catherine Banet from the University of Oslo's Faculty of Law explains why liability in terms of shipping had been so uncertain: "When the primary 2009 EU legislation on CCS was ratified, it didn't take shipping into account. It's now a very relevant part of the North Sea research and development projects, but for us to move forward we must understand if there are any legislative barriers that would impede its operation, and if so, how we can deal with those."

Several PhD and Master students have been working through the process. Researcher Alice O'Brien's thesis recommends that the HNS Convention must enter into force before large-scale CO_2 shipping becomes a reality. That's in order to provide consistent liabilities to shipowners and ensure predictable compensation for victims. She also recommends that shipping be included within the CCS Directive and EU ETS to protect the environmental integrity of the CCS value chain and ensure there is an economic inventive to engage in shipping-based CO_2 transport.

Catherine is pleased with the work to date. "We have identified a lot of relevant issues and have been able to make concrete recommendations. Clarification is needed on these issues to provide the legal certainty for all actors, including governments and operators, to build and run a full commercial CCS chain using shipping," she says.

STUDYING THE OUTDOOR LAB OF SVALBARD

According to the Climate in Svalbard 2100 report, average annual temperatures on Svalbard have risen by 4°C since 1971, with winter temperatures rising by more than 7°C. The remote Arctic archipelago is one of the places hardest hit by the early impact of climate change. The rate of glacial calving has increased rapidly. Meanwhile, the increasing number of avalanches have impacted human life, while native wildlife from reindeer to polar bears have been affected by profound seasonal changes.

Studying the Outdoor Lab of Svalbard

Mark Mulrooney, Postdoc NCCS

Peter Betlem, PhD NCCS

NCCS researchers are now studying Svalbard's subsurface and outcrops to gain important integrity data that will help to successfully deliver carbon capture, transport and storage (CCS), a critical climate change mitigation technology. For instance, data for rock physics models are needed to help us better detect and predict the behaviour of fluid flow following any potential breach.

The research attracted interest from far and wide, and not just from scientists. A large male polar bear paid two visits to the field researchers at Deltaneset, causing some disruption to the schedule. However, the scratches and scrapes on the old UNIS cabin used as the research base reminded everyone of their status as guests.

Why Svalbard?

Subsurface saline aquifers in the Norwegian sector of the North Sea that have been earmarked for injection and storage of CO_2 date back many millions of years to two phases of continental rifting. These rift events lead to the development of sedimentary basins which now offer porous and permeable storage formations for potential CO_2 storage. Assessing the caprock integrity is difficult given limited subsurface data, but is much more feasible at the geologically-similar succession on Svalbard.

This succession had previously been investigated as a caprock by the University Centre in Svalbard's (UNIS) CO_2 lab. This gave NCCS researchers a wealth of multi-scale, multi-disciplinary data to build on.

Field work to fill knowledge gaps

Researchers from across Norway came together on Svalbard last year to conduct important caprock integrity analysis. The research, part of NCCS Task 9, aims to fill knowledge gaps about how subsurface faults and fractures will influence CO_2 migration and containment.

Thanks to the NCCS mobility fund, the University of Oslo's Mark Mulrooney spent four weeks in Svalbard in collaboration with UNIS' Dr Kim Senger. "I participated in a field campaign followed by computer lab work aimed at synthesizing outcrop observations with the pre-existing Svalbard geomodel established over the past decade by the UNIS CO_2 lab. The fundament of the research is to assess the reactivation potential of heterogeneities intersecting the caprock and as such determine caprock integrity," says Mark.

Thousands of measurements from faults and fractures

During a two-week field campaign, thousands of orientation measurements from faults and fractures were taken as well as information on aperture, mineral infill, vertical extent and frequency.

Work will continue, but key initial findings include the presence of low angle normal faults in the lower part of the Agardhfjellet Formation, and low angle reverse faults in the upper part. Higher fracture frequency up section is also apparent. These structures are too small to image with conventional seismic surveys but can significantly influence fluid flow. As such it is important to investigate these structures in the field.

Digitising the larger structures that intersect the Agardhfjellet Formation and compiling subsurface parameters derived from the UNIS CO_2 lab (e.g. in situ stresses and pore pressure) reactivation potential could be calculated. "The caprock integrity analysis results show subsurface faults are not prone to reactivation. The variable topography of Svalbard has some effect on the in-situ stress magnitudes at depth, however, it never compromises fault integrity," explains Mark. Future work hopes to analyse how the caprock will respond on the scale of individual fractures.

Rock physics models help us understand the unknown

Peter Betlem is a PhD candidate in Arctic Geology at UNIS and the University of Oslo. He uses much of the data gleaned from Svalbard to assess the multi-physical detection limit of fluid flow through caprock sequences.

"Rock physics models provide a link between known rock properties and the unknown, resulting properties picked up during seismic and electromagnetic exploration. The more data we acquire on a sample, an interval, or even a formation, the better we can correlate these different properties to one-another. In turn, this allows us to better predict properties for unsampled intervals, provided at least some of the properties are known in the first place," explains Peter.

A digital success story on Svalbard

Eight fully cored boreholes supplemented by wireline logging provided many key properties for characterisation, but additional work was needed to fill knowledge gaps. The qualitative density wireline logging was one such gap. Rather than use the established method that risked destroying the samples, Peter and his colleagues experimented with structure-from-motion (SfM) photogrammetry.

Much like how our own eyes work, photogrammetry allows for the estimation of 3D structures from 2D image sequences. Ground control points (GCPs) add real world coordinates to the synthesised 3D models and allow for sub-millimetre resolutions in the process. After several weeks of finetuning the workflow, digital drill core models were acquired with sub-millimetre spatial errors. Subsequent analysis from the Norwegian Geotechnical Institute in Oslo showed that the bulk volumes and densities derived digitally closely matched the geotechnical measurements.

Following this success, the team is now expanding this digitisation effort to cover the entire cored caprock sequence of the Longyearbyen CO_2 Lab by digitising drill cores at one metre intervals. "Not only does this provide us with the data needed to quantify the density logs, it also enables the establishment of the very first digital drill core library. All acquired digital drill core models will eventually be integrated with Svalbox.no, an initiative established to provide an interactive frontend to all geoscientific data originating from Svalbard," says Peter.

CO_2 research on Svalbard

Research into CO_2 and Carbon Capture, Transport and Storage (CCS) technology has been carried out by the University Centre on Svalbard (UNIS) since 2007. In early 2012, the UNIS CO_2 Lab was founded as a spin-off company, fully owned by UNIS. The lab aims to take advantage of Longyearbyen's closed energy system, which is powered by Norway's only coal-fuelled power plant that also delivers heat to the town's buildings.

The small community could demonstrate the full CCS value chain becoming a global showcase for how to take care of CO_2 from source to solution. Such knowledge and competence acquired in Longyearbyen can be utilised on global projects. The studies of sub-surface structures will benefit storage projects elsewhere, including the research taking place within NCCS.

RESEARCH PLAN

NCCS has the ambition to be dynamic, i.e. readily suited to shift scientific focus to adapt the CCS world around us. The NCCS industry-driven case-oriented concept has been developed with industry partners, ensuring strong industry ownership and governance of the Centre. The scientific tasks are to be assessed and reviewed often. The Technical Advisory Committee (TAC), the Operations Centre (OC), and the Board will have key roles in decisions at the gate review. NCCS can use this method to regularly evaluate the R&D profile to maintain research competitiveness, and to align with the CCS world by taking the learnings and needs from large-scale and demonstration projects (e.g. the Norwegian Full-scale CCS chain) and adapting the R&D direction accordingly.

Well-structured research plans, reviewed and revised during the Deployment Case Gate Reviews, will set the direction for what is required to advance technologies to a higher Technology Readiness Level (TRL).

Research will contribute to advancing TRL either directly in the more applied research tasks, or indirectly by supplying fundamental insights and mathematical models to other tasks along the deployment case chain. This will allow quantification, and thus give increased confidence and safety, and reduced cost. Data and knowledge from industry (e.g. Aker, Norcem and Krohne) and the Boundary Dam Full-scale Project will also play a key role in increasing understanding and advancing TRL.

This broad scientific approach, involving all key elements of the CCS chain, requires a considerable effort for NCCS to be able to significantly contribute to fast-track deployment of CCS in Norway and Europe. To generate the new knowledge required to overcome the barriers against CCS, a number of carefully chosen PhD topics are tightly integrated in the centre.

INNOVATION STRATEGY

NCCS' main goal is to fast-track CCS deployment by timely delivery of safe and cost-efficient CCS technologies. This is facilitated by promoting an innovative environment through concreted cooperation between scientists and industry partners. The potential for spin-offs, start-ups or license agreements will be continuously monitored. As an international CCS research hub, NCCS is built to promote open innovation processes where companies involved in the Centre will be able to commercialize ideas and emerging technologies from outside their company boarders, building on others' ideas and even bringing ideas from NCCS into new and emerging markets. This model optimizes innovation and technology output across company boarders and increases the potential gain for each company involved, as the pool of ideas and concepts emerging from NCCS will be larger than that of each company.

Innovation may be defined as a product, a technology, a component, a process, a model, a concept, an experimental facility or a service that is new or significantly improved with respect to properties, technical specifications or ease of use. This gives many potential routes for commercialization – from a single actor, via joint venture, to broad implementation for several stakeholders or markets. Thus, commercialization following the open innovation model requires a comprehensive intellectual properties (IP) strategy to maximize value creation for each involved company. NCCS will aim to disseminate results among partners whenever possible and at the same time secure IP rights for each partner where necessary.

NCCS maintains continuous focus on innovation and technology transfer. A dedicated Innovation and Technology Transfer Task intends to be an enabler within the Centre, striving to promote a good environment for developing innovations through engaged cooperation between researchers and industry partners on specific topics.

In 2018, seven selected innovations from NCCS and its predecessor BIGCCS were investigated to estimate potentials for cost reductions if the new innovations were successfully implemented in one full scale CCS project, and to provide an indication of the potential value of CCS research investments. Based on scenarios for CCS deployment developed from IEA and UN IPCC scenarios, it can be shown that the potential value creation from estimated cost reductions alone by far exceeds the investments in the two research centres.

In 2019, the Innovation and Technology Transfer Task kick-started the *NCCS Impact Study*, where four tasks in NCCS have been assessed for potential impact. They are presented in the next chapter.

INNOVATIONS AND IMPACT OF NCCS RESEARCH

Maximising impact from our research is an important task for NCCS. In this study, we have selected four of the twelve research tasks and assessed the potential impact of the research and innovation given that the research is successful. In this context, impact can be measured along several axes. Examples include reduced emissions, economic impact (increased value creation, saved costs), improved decision making, saved energy, and industrial potential.

The study illustrates how the research and expected innovations will impact CCS chains and society when applied. The reference system is the envisaged CCS network in Europe by 2030. It is an ambition to perform the same study on all research tasks in NCCS throughout 2020.

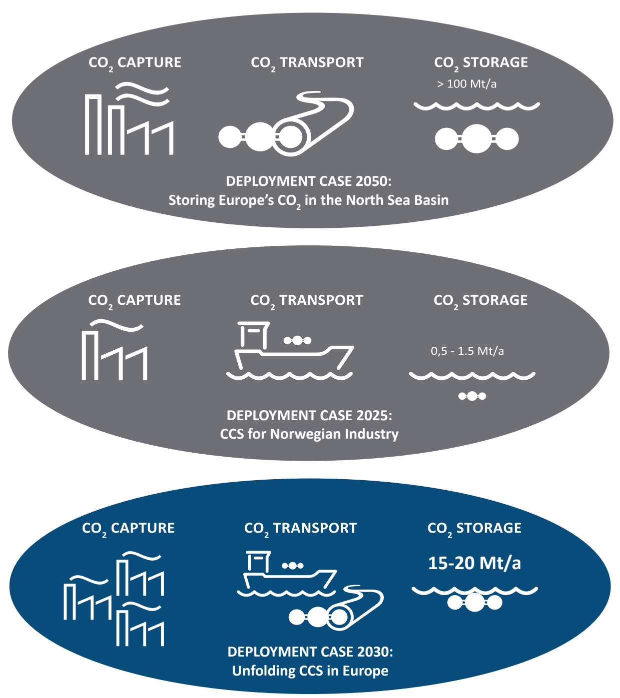
Research within CO_2 capture, transport and storage is multi-disciplinary and covers a wide range of topics. Consequently, the outcomes have different characteristics with respect to type of innovation, maturity and applicability in the CCS chain. The innovations covered in this study mainly fall under four categories: 1) new technology, 2) models and calculation tools, 3) new methods, and 4) new standards and guidelines.

NCCS Deployment Cases - directing research for maximum impact

NCCS originally defined two CCS deployment cases (DCs) to help structure and align the research, and support NCCS in fulfilling its ambition to overcome critical barriers and accelerate CCS deployment. **NCCS DC2025 - CCS for Norwegian Industry** is similar to the Norwegian Full-scale Project and includes CO_2 capture from industry sources and transport with ship to ensure a flexible solution for CO_2 storage on the Norwegian Continental Shelf (NCS). One storage site in offshore aquifers is anticipated, with a capacity of 1-1.5 Mt/year in 2025.

The second deployment case, **NCCS DC2050 - Storing Europe's CO_2**, comprises captured CO_2 from numerous sources in Europe and transport via a pipeline network to Norwegian storage sites in the North Sea. Several major storage sites are foreseen, some with an opportunity for EOR, with a storage capacity of ~100 Mt/year by 2050.

For this NCCS impact study a third deployment case is defined to serve as basis for analysis: **NCCS DC2030 - Unfolding CCS in Europe**. DC2030 incorporates all European CCS projects implemented, under construction and those planned to be in operation within 2030. It includes industry sources, power generation, natural gas processing and H_2 production. A combination of ship and pipeline transport of CO_2 to aquifers and depleted gas fields ensures flexibility. Capacity in 2030 is estimated to be 15-20 Mt/year, with the ambition to increase it to more than 40 Mt/year after 2030.



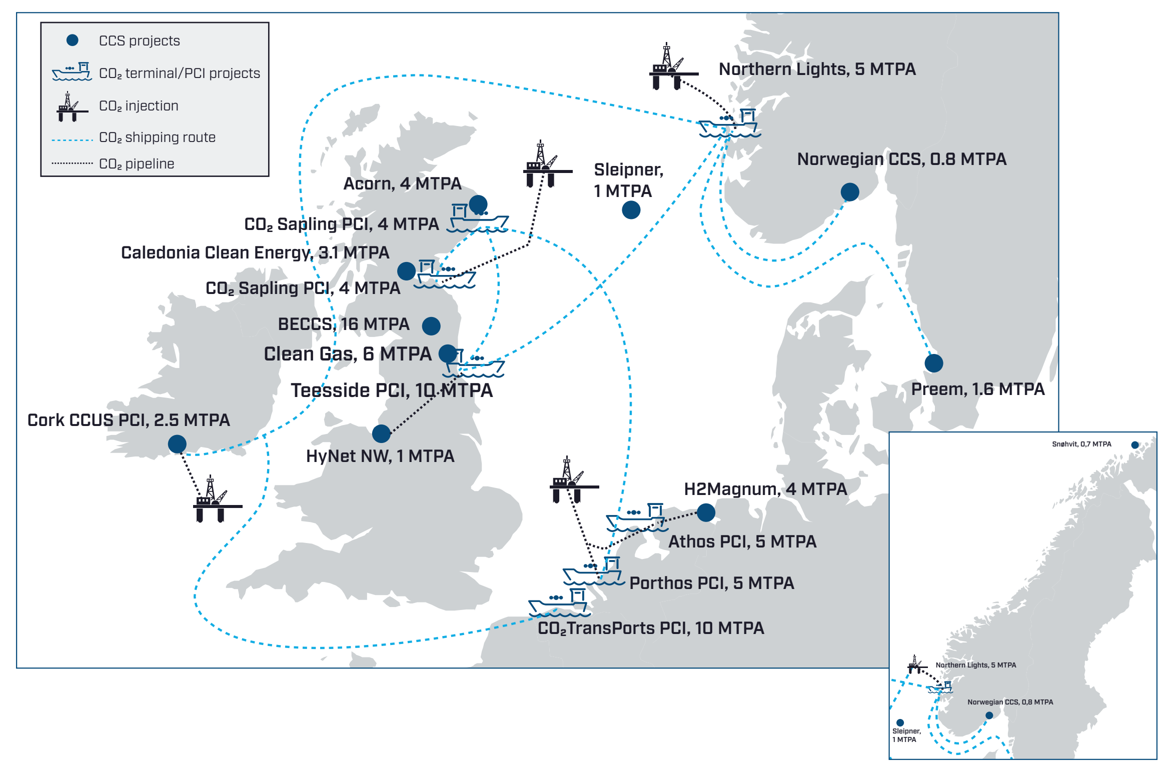
Projects included in NCCS DC2030 - Unfolding CCS in Europe *

	Facility	CO_2 capacity, MTPA
CCUS projects		
1	Norway full chain CCS, NO	0.8
2	Sleipner, NO**	1
3	Snøhvit, NO**	0.7
4	Preem, SE	1.6
5	Acorn CCS, UK	4
6	Caledonia Clean Energy, UK	3.1
7	Clean Gas Project, UK	6
8	BECCS, UK	16
9	HyNet North West, UK	1
10	Hydrogen 2 Magnum, NL	7.5
11	Cork CCSU, IR	2.5
	SUM	**~44**

Open access Transport and Storage infrastructure		
12	Northern Lights, NO	5
13	CO_2 Sapling, UK	4
14	Teesside Collective, UK	10
15	Athos, NL	7.5
16	Porthos, NL	5
17	CO2TransPort, BE	10
	SUM	**~42**

* Based on Facilities Database (Global CCSI), PCI Interactive map (EC), Projects' webpages, etc.

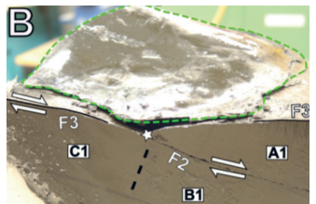
**In operation: CO_2 capture and storage



Expected impact from selected cases

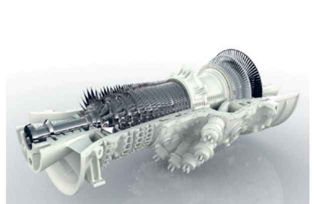
Case A
Solvent loss reduction

Main impact:
Reduced OPEX and improved safety in operation and operational environment



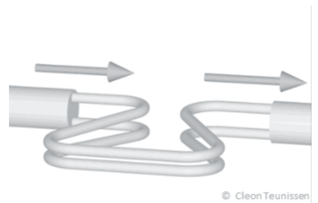
Case B
Increased storage capacity with improved fault models

Main impact:
Reduced uncertainty resulting in improved safety for storage sites and increased storage capacity



Case C
Hydrogen-firing of gas turbines

Main impact:
Novel technology for combustion of 100% H_2 in gas turbines, allowing large-scale emission free power generation at high efficiency (>60%)



Case D
CO_2 fiscal metering

Main impact:
Validated fiscal meters for CO_2 with improved accuracy for correct financial settlements along the chain

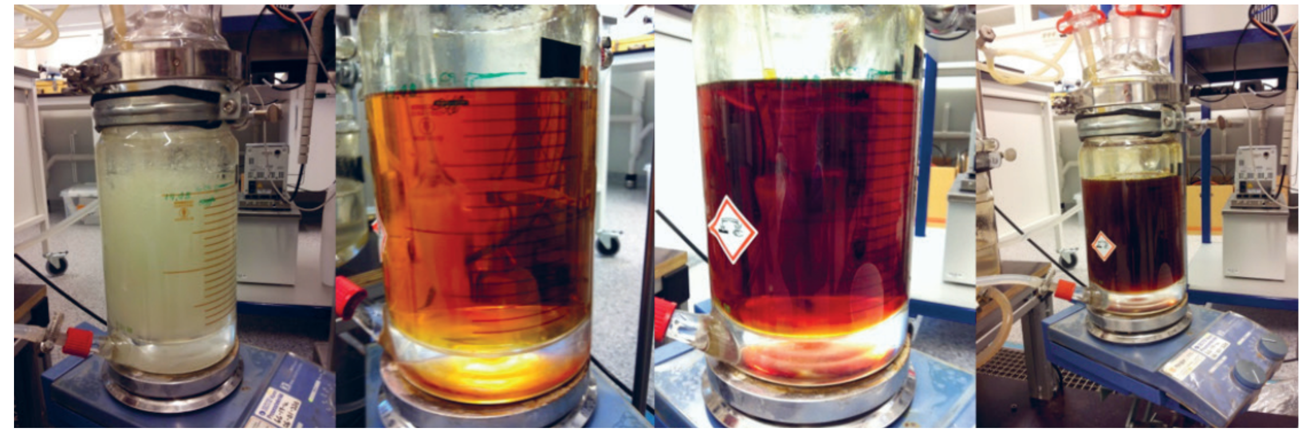
Case A: Solvent loss reduction (Task 2)

The challenge:
During chemical absorption, CO_2 present in a flue gas is absorbed and chemically bound to a solvent. The reaction is reversed during solvent regeneration and the solvent is reused to absorb CO_2. Tiny amounts of the solvent will react with other compounds in the flue gas forming compounds that cannot be regenerated. Over time, these reactions lead to loss of capture efficiency and could cause problems such as corrosion, fouling, foaming and increased emissions.

The innovations:
The work investigates several mitigation methods including:

- Identification of solvents with higher chemical stability to minimize solvent loss
- Mitigation technologies, like removal of oxygen from the solvent as these components will enhance degradation
- Better understanding the degradation and corrosion mechanisms, allows development of innovative, new technologies to tackle the challenges

Potential impact:
Base case for illustration: 2 million tons per year (MTPA) CO2 captured from two coal gasification combined cycle (CGCC) power plants using 30% MEA-based solvent technology. With the MEA cost of €2/kg and solvent degradation rate of 2 kg MEA/ton CO2, the cost of solvent loss is €8 M/year.



Initial **20 hrs** **93 hrs** **187 hrs**

Example on solvents colour change for an oxidative degradation experiment.

Estimated effect from implementing NCCS innovations for oxygen and iron removal is up to 50% lower degradation of MEA based solvent. This would give **potential savings** up to **€4 M/year** in replacement cost of the active solvent components.

In addition, fundamental knowledge developed in Task 2 on structure - degradation relationship for various amines would enable selecting a stable solvent at early stage of the solvent development based on predicted degradation behaviour.

Case B: Increased storage capacity with improved fault models (Task 9)

The challenge:
Implementation of large-scale CO_2 storage will require utilization of a wide range of storage reservoirs including faulted reservoirs with structural traps. The sealing properties of faults are challenging to predict, and conservative estimates and high uncertainty may limit the total injection volume or even disqualify a storage site. Existing industrial models have limitations when addressing fault risk related to CO2 injection in faulted aquifers.

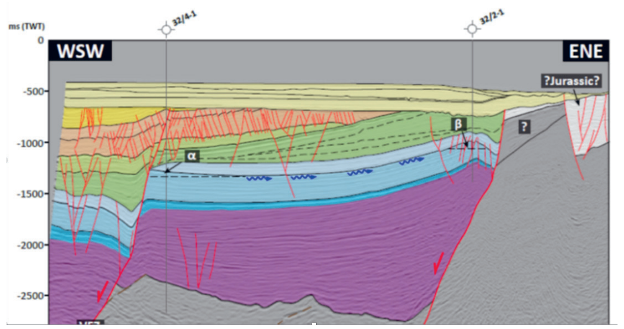
The innovation:
Development of an improved fault derisking framework that includes dynamic pressure changes related to CO_2 injection and addressing along-fault fluid migration is a main ambition of NCCS Task 9. Such a framework can:

- Reduce uncertainty related to fault properties
- Increase confidence in site integrity and confinement
- Enable qualification of increased storage capacity.

Potential impact:
The development of the Horda Platform area for CO_2 injection showed that high uncertainty in existing fault seal prediction models for shallow, fault-bound aquifers like Smeaheia, limits the capacity and provides major obstacle for site qualification. The Norwegian CO_2 storage atlas (NPD, 2012) indicates around 40 Gt

storage capacity in Norwegian North Sea aquifers. The effective volumes found suitable for safe and long-term storage during technical maturation may be as low as 10% of the estimated capacity.

For the Norwegian **North Sea** this gives a suitable safe capacity around 4 Gt. Assuming this volume could be increased with roughly 10% if risk related to fault sealing is reduced, a total 400 Mt increase in storage capacity can be estimated, **enabling 20 years of storing 20 Mt CO2/year (NCCS DC2030)**. Improved fault seal models and reduced uncertainty is a necessary, although not sufficient, step towards qualification of additional storage capacity.



Seismic section with fault interpretation for Smeaheia (ref. Mulrooney et al, in prep).

Case C: Hydrogen-firing of gas turbines (Task 5)

The challenge

Hydrogen can be used for clean and highly efficient power generation with minimal CO_2 footprint. Improved fuel flexibility of gas turbine combustion systems is desirable, e.g. combustion of 100% H_2 without the need of fuel diluents such as N_2 or steam injection. Known challenges for H_2 combustion are:

- Flashback (off-design flame displacement): higher risk due to higher flame speed
- Autoignition (off-design early ignition): higher risk due to lower ignition delay time
- Combustion dynamics (thermo-acoustic instabilities): well-known thermo-acoustic amplitude level and frequencies for natural gas combustion are modified by hydrogen addition
- NOx emissions: due to higher flame reactivity, temperature and different structure/stabilization.

The innovation

Combustion technology development leads to potentially novel solutions to allow retrofit of existing gas turbines for combustion of 100% H_2:

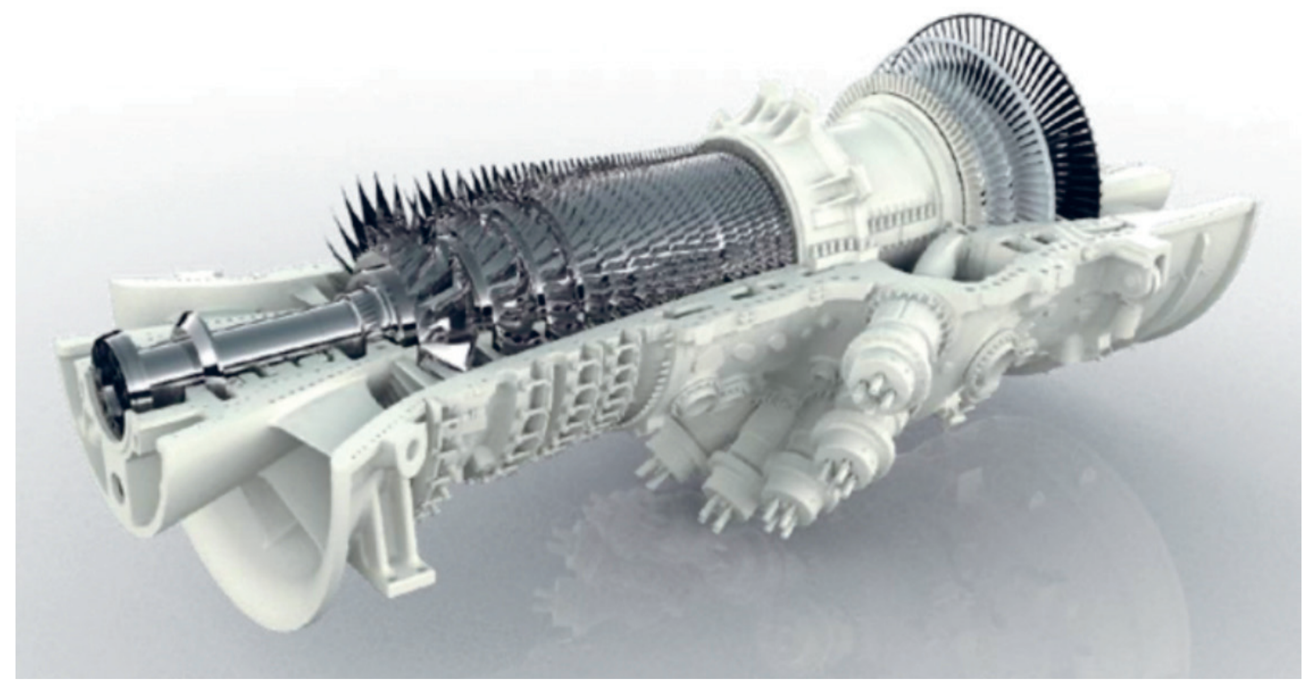
- H_2-rich fuel injection system design
- Combustion chamber design
- Expertise in H_2 combustion control

Potential impact

- Efficient large-scale power generation based on H_2 from natural gas with CCS
- Compared to available technology the research aims to enable combustion of 100% H_2, saving fuel costs by not needing diluents as N_2, usually at a ratio of 10 kg N_2 per kg H_2 to be combusted.
- Hence, achievement of carbon-free power generation that is both clean (low NOx) and thermo-dynamically efficient (>60%), at large scale (>1000 MW).
- Bridge H_2 production from natural gas w/CCS and H_2 from renewable sources, at large scale.

Base case for illustration: Baseline natural gas-fired combined cycle gas turbines (CCGT): 750 MWe at 60% efficiency. Key assumptions:

- 10 kg N_2 per kg H_2 are the dilution requirements in



Gas Turbine from Ansaldo, GT36.

conventional non-premixed systems (overall plant efficiency loss 4%)

- Firing temperature reduction in premixed systems with advanced staging (sequential/reheat) results in 1% overall plant efficiency loss
- H_2 cost is €1.5/kg and cumulative yearly energy production target is 6.24 TWh

Reduced fuel costs are related to savings due to higher overall plant efficiency for the dilution-free advanced staging combustion system and estimated at **€39 M/year.** The cumulative yearly H_2 fuel cost for conventional N_2-diluted H_2 combustion system is **€544 M**, while the cumulative yearly H_2 fuel cost for pure H_2 combustion system with advanced staging is **€505 M**.

There will be considerable additional savings because of unnecessary process equipment for diluent (nitrogen or steam) preparation and **reduced emissions** as the CO_2 avoided, if H_2 is produced without CO_2 emissions, of **2.1 Mt/year**.

Case D: Fiscal metering and CCS fluid property research (Task 8)

The challenge:

The European Union Emissions Trading System (EU ETS) is a pan-European system for trading greenhouse gas emission allowances. To be able to report avoided CO_2 emissions through CO_2 capture and storage in the EU ETS, traceable metering of CO_2 is critical, and hence a business driver for CCS. In addition, custody transfer in CCS needs metering. Currently, no fiscal flow meter technology has been verified at relevant flow rates and conditions for large-scale CO_2 management.

The innovation:
The ongoing research in NCCS on fluid properties of CO_2, modelling as well as targeted experimental investigations, and design of an industrial scale test centre, aims for fiscal metering technology that can ensure traceable measurements for CO_2 with quantified uncertainties. This can enable qualification of fiscal flow meters for CCS.

Potential impact:
Qualified fiscal metering technology and procedures will make CCS relevant for EU ETS. For instance, those who have implemented CO_2 capture can avoid buying allowances to emit CO_2 (European Union Allowances (EUAs)) under the EU ETS or sell EUAs they already have. With an increasing number of CCS projects and increasing costs of emission allowances, the total value of allowances will grow significantly.

For instance, in the Norwegian Full-scale Project the conservatively estimated annual value of CO_2 traded under ETS can amount to €20 M/year (800 k tonCO_2/year using today's ETS carbon price of €25/ton CO_2). For NCCS DC2030, the annual value of CO_2 traded is €700 M/year (20 mill. tonne CO_2 /year using the ETS carbon prices projected in "EU Reference scenario 2016"; ca € 35/ton CO_2).

NCCS aims to enable verification and validation of commercially available fiscal meters for measurements of CO_2 flow, e.g. from a capture site, certifying that the uncertainty of the stored CO_2 mass is below ETS requirement, currently at 2.5%. This will qualify the company for release of EUAs. In addition, innovations in NCCS will improve the accuracy of CO_2 metering systems, and, hence, the financial settlement for the actors along the chain will be more correct. For instance, 1% accuracy improvement would mean that:

- For the Norwegian Full-scale Project, the correct settlement implies that values around **€200 k/year** are received by the rightful party.
- In DC2030 the correct settlement can imply that **€7 M/year** is received by the rightful parties.

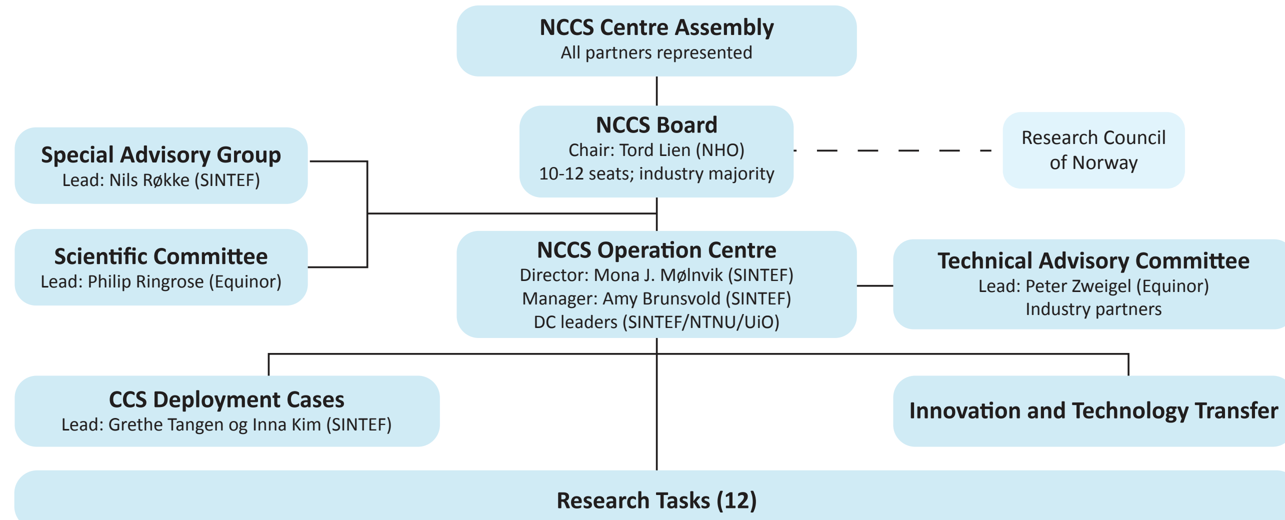
For complex CCS chains and systems, the settlements could potentially be larger as there will be multiple parties along the value chains needing custody transfer and thus, depending on accurate fiscal metering.

KROHNE Optimass 6400 Coriolis flowmeter

Contributors to the NCCS Impact Study
Technology providers involved in development of presented innovations are Ansaldo Energia (Case C), and KROHNE and Baker Hughes (Case D). The research is supported by the user industry represented in NCCS: Equinor, Total E&P, Lundin, Vår Energi, Gassco, Norcem, and Oslo Kommune. The study is conducted by SINTEF, TNO, NGI, NTNU and UiO.

ORGANISATION

Organisational Structure



Partners

RESEARCH PARTNERS

British Geological Survey

Norges Geotekniske Institutt

Norwegian University of Science and Technology

Ruhr – Universität Bochum

SINTEF
SINTEF Energy Research
SINTEF Industry

TNO

Technische Universität Munchen

The University Centre in Svalbard

University of Zürich

University of Oslo

The University of Western Australia

INDUSTRY AND VENDOR PARTNERS

Equinor

Gassco

Shell Global Solutions International B.V.

TOTAL

Norsk Olje og Gass

Aker Solutions

Ansaldo

CoorsTek

Quad Geometrics

Larvik Shipping

Krohne

NORCEM

Oslo Kommune, gjenvinningsetaten

Lundin Norway

Vår Energi

ASSOCIATED PARTNERS

ECCSEL

US Department of Energy

UKCCS

Scottish Carbon Capture & Storage

Lawrence Livermore National Laboratory

Sandia

Massachusetts Institute of Technology

Cooperation between partners

"Task families"

An industry led centre is dependent on effective arenas and processes for cooperation with industry partners. An important and highly successful measure was the establishment of "task families". The task families include specialists from industry and research actors with interest in the topics addressed. Through workshops, Skype meetings, and webinars, all partners can contribute to technical discussions and influence the ambitions for next year's work program. NCCS includes a number of industry companies and all are active contributors in one or more task families.

Consortium Days

The prime event in the NCCS calendar is the annual Consortium Days staged in fall. Here several representatives from all partners meet to review and discuss this year's results. The 2019 Consortium Days were held October 22-33 in Trondheim with close to 100 participants. The event combined a mix of pitches from the tasks, extended presentations in plenum, posters, and breakout sessions to go even deeper into the technical results.

Pictures from the NCCS Consortium Days 2019.

Webinars

Webinars have proven an effective tool to convey and discuss results from research activities. The benefit of not having to travel saves time and makes sharing of results more cost effective. So far, around 20 webinars have been held, and the goal is that each research task sets up at least one webinar per year.

Scientific Committee (SC)

The NCCS Scientific Committee comprises eight members from leading academic institutions in the fields of CO_2 capture, transport and storage. Its mandate is to guide the scientific progress of the Centre and to comment on the overall scientific focus and direction of NCCS. As part of its work the SC conducted a review of the 12 tasks in the NCCS in June 2019, and then fed the assessment back to the Centre. The main advice given at this this point was:

- Overall good science is being done, but the task leaders and researchers need to be better at communicating the potential impact of their research and technology goals.
- More efforts should be made on integrating the 12 tasks with the common goals in the deployment cases.

In particular, the SC emphasized the importance of communication of science. "Science is beautiful when it makes simple explanations of phenomena or connections between different observations." *(Stephen Hawking)*. The group agreed to set up a 'best paper' review and award system in 2020 to help profile some of the excellent research being done by the Centre.

Over the next four years the SC will focus on ways of building the NCCS vision and ensuring that this unique collection of institutes, universities and industrial partners generates high-impact research and innovation. The next review is planned for autumn 2020.

The members of the SC are: Prof. Marco Mazzotti, ETH Zurich, Switzerland; Dr. Curtis M. Oldenburg, Lawrence Berkeley National Laboratory, USA; Prof. Martin Trusler, Imperial College London, UK; Prof. Sally Benson, Stanford University, USA; Prof. Nigel Bankes, The University of Calgary, Canada; Dr. Tip Meckel, University of Texas at Austin, USA; Dr. Ziqiu Xue, RITE Research Centre, Japan; Prof. Philip Ringrose, NTNU & Equinor, Norway.

Technical Advisory Committee (TAC)

The Technical Advisory Committee (TAC) is a body of NCCS' governance structure with the main task to advice the Board on matters of special interest for the industry partners. Every industry partner has a representative in the TAC, and it is led by one of the industry partners (Equinor).

The main input of the TAC to the work done in NCCS has been three-fold:

- Key contributor in the yearly phase-gating process, where achievements so far are evaluated and input is given about which topics should be prioritized in future work. This has resulted in changes in scope and budget allocations for various tasks.
- Quality control, particular with respect to industrial relevance, should be visible in the Annual Work Plans (AWPs) of the technical tasks.
- Advice to the Board on the use of unallocated industrial funds. These funds have so far mainly been used to co-fund research projects largely funded by the Research Council of Norway, which complement research carried out in the NCCS tasks.

The TAC members have already agreed to shift focus to more strategic level. This means that we will rather address the overall scientific and technological content of the Centre and of the technical tasks. The detailed content of AWPs for each task will be the responsibility of the individual task families; the TAC will only have a final check of consistency of the AWPs with the overall prior input given by the TAC.

The TAC has an ambition to increase its activities to ensure even more industrial relevance of the research carried out in NCCS. In March 2020, we will review achievements so far and discuss strategic input to the shaping of the last half of the lifetime of this FME. New industry partners have joined NCCS, and it will be useful to include their ideas.

NCCS has already developed some promising technologies, but typically to low TRL levels. One important task for the TAC will be to advice on paths for maturation of selected technologies to higher TRL levels, with the ultimate goal to implement these technologies at industrial scale. Industrial application of knowledge and products developed in the Centre is at the core of NCCS' contribution to the energy transition. Industry partners have a strong interest – and responsibility – to support this important contribution.

RESULTS FROM RESEARCH TASKS

Research in NCCS addresses challenges critical to realization of two Deployment Cases: CCS for Norwegian Industry, and Storage of Europe's CO_2 in the North Sea. The work is organised in 12 tasks, spanning the entire CCS value chain. An extra activity, Innovation and Technology Transfer, serves all 12 research tasks.

NCCS includes a comprehensive education program with fellows integrated into the Centre's research tasks and many of the activities use laboratories established as part of ECCSEL, a distributed research infrastructure for CO_2 handling. The following pages present highlights from 2019.

The CO_2 value chain and legal aspects (Task 1)

The Task seeks to demonstrate the importance of CCS to decarbonize the energy and industrial sector to reach the Paris Agreement target. It will provide recommendations on the best measures to cut CCS costs and assess shortcomings in the current legal framework applicable to CCS operations at national and international levels. This will help enable a faster and cheaper deployment of CCS technology.

www.sintef.no/NCCST1

THE CO_2 VALUE CHAIN AND LEGAL ASPECTS **(TASK 1)**

Understanding and planning for uncertainties

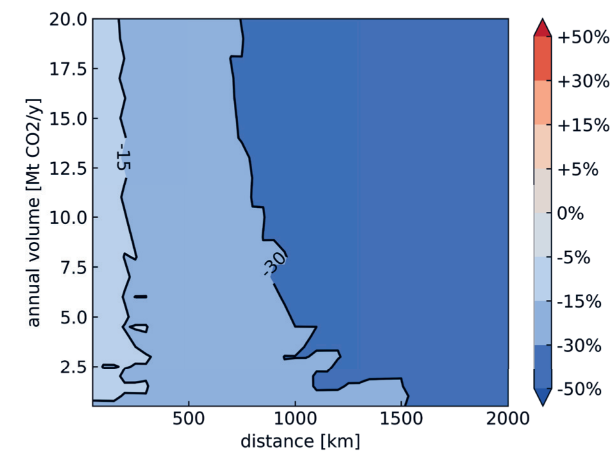
In 2019, we developed a new approach for design of the CCS chain under uncertainties. This was done to better understand the impact of uncertainties on CCS chain performance, and to enable better design than when uncertainties aren't planned for. This approach was demonstrated over the case of a waste-to-energy plant. It helped us better understand the range of capture costs that could be achieved, hence enabling more informed decisions about financial risks. Furthermore it enhanced our understanding of how CCS infrastructure from a waste-to-energy plant could be designed more robustly to remain cost-efficient even in the case of less likely conditions.

Shipping CO_2 at 7 bar could enable significant cost reduction

To reduce conditioning and transport costs of CO_2, we identified cost-optimal transport conditions (temperature and pressure) for transport of CO_2 via ship. There has been a lot of discussions on whether shipping at 7 bar is more cost-efficient than 15 bar, but no study has satisfactory concluded on this. We studied if the 7 bar shipping option could be more cost-efficient than the current commercial 15 bar technology. Our work concluded that the 7 bar shipping option could enable significant cost reduction for a wide range of combinations of transport distances and capacities, both in the case of pure CO_2 or CO_2 with impurities after the capture process. The work showed that the 7 bar technology can reduce costs with 15% and above in most cases. Furthermore, for longer distances cost reductions beyond 30% can be achieved. A paper focused on the liquefaction process aspects of this work was published in 2019 in the International Journal of Refrigeration and a manuscript summarizing the complete results and conclusion will submitted for publication in 2020.

Legal aspects to enable CCS chains based on ship transport.

Task 1 investigated the legal framework of CO_2 shipping for CCS and identified one point needing urgent attention. According to the current frame of the European Emission Trading Scheme, CCS based on ship transport may not provide credit for the avoided CO_2 emissions. This framework must thus be revised so CCS projects based on CO_2 shipping are eligible for financial credit under the European Emission Trading Scheme and to expressly provide for the ship transport of CO_2. The present legal solution is unsatisfactory. It creates a legal risk and potentially hinders investment.



Cost reduction in CO_2 liquefaction and transport that could be achieved by considering the 7 bar shipping instead of 15 bar shipping: for pure CO_2 and in the case in which ships larger than 10 000m^3 can be built for the 15 bar technology.

Solvent technology – environmental issues (Task 2)

This Task addresses the challenges related to solvent technology, with a focus on environmental issues. We work to better understand the degradation of solvents by investigating which factors have the highest impact on the stability of amines (organic compound derived from ammonia), which are used to capture CO_2 from various flue gas sources. Furthermore, the Task contributes to the reduction of operational- and investment cost by indicating amines with higher stability and developing technologies to control and monitor solvent stability. Higher stability of solvent means reduced cost, reduced emissions, improved lifetime of both material and solvent, improved safety for employees and reduced environmental impact.

www.sintef.no/NCCST2

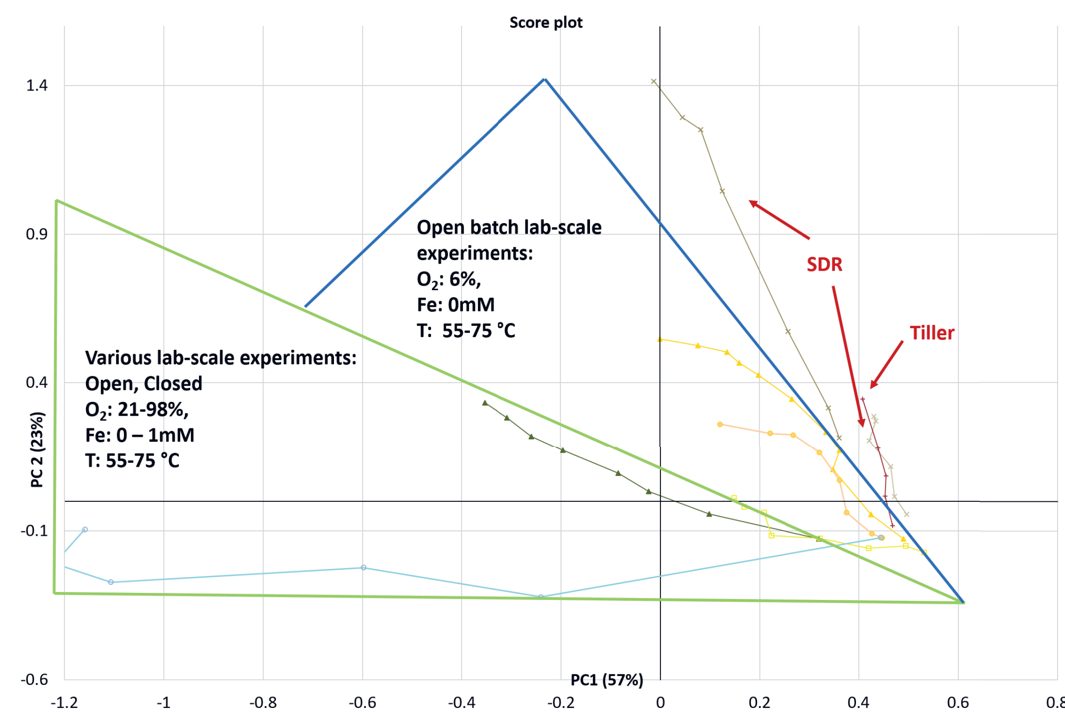
SOLVENT TECHNOLOGY – ENVIRONMENTAL ISSUES **(TASK 2)**

The technology developed in Task 2 will positively impact CCS' already positive effect on the environment and reduce CCS costs through developing more stable solvents with longer lifespans.

Oxygen solubility

Throughout 2019, different factors influencing oxygen solubility have been investigated and several methods to measure oxygen solubility have been evaluated.

Oxygen reduces the stability of the solvent and if oxygen solubility could be measured and a correlation between oxygen solubility and degradation could be identified, a faster method to evaluate chemical stability of new solvents would be available. The limitations and opportunities with online oxygen sensors have been identified and recommendations for their applicability were made. Online oxygen sensors (analytical instrument measuring oxygen concentration) have shown to be very useful for stable



Score plot from Principal Component Analysis (statistical method to investigate dataset) over different lab experiments (batch and solvent degradation rig- SDR) and Tiller pilot (x-axes-Principal Component 1, y-axes-Principal Component 2). The figure shows that the open batch lab-scale experiments at low O2, in regard to degradation compounds profile, shows highest resemblance to cycled experiment (SDR) and pilot demonstration (Tiller).

solvents, while measurements of oxygen concentration in fast degrading solvents is challenging with all available measurement methods.

DORA - Dissolved oxygen removal apparatus

Oxygen from the flue gas is a contributor to decomposition of amine solvents, the decomposition mechanism is also more difficult to follow since the initial step involves radical reactions. We've performed lab scale experiments to demonstrate Dissolved oxygen removal apparatus' (DORA) ability to reduce oxygen concentration in the solvent. It was demonstrated that ammonia concentration is reduced when DORA is used, which indicate less decomposition of the solvent. The technology has been qualified for testing at a larger scale pilot campaign (1 kg CO_2/hour) for a longer time period - to take place in 2020.

Technologies like DORA is an example of both the cost and environment aspect of CCS. Our results thus far show that DORA will reduce solvent loss through mitigating solvent degradation. Less solvent loss means less environmental impact and costs saved, e.g. by not having to handle as much waste and consuming less solvents.

PLS-model validated

The Partial Least Square (PLS) model (statistical method used to evaluate data sets) developed in Task 2 in 2018, was validated in 2019 using samples from pilot projects around the world. It was proved that the PLS-model accurately predicts the concentrations of ethanolamine (MEA) and CO_2 in the solvent, these components are important input to daily operation of the pilot plant. It can therefore potentially be used for online solvent analysis using Fourier-transform infrared spectroscopy (FT-IR) technology. Infrared spectroscopy exploits the fact that molecules absorb frequencies that are characteristic of their structure and functional groups give rise to characteristic bands both in terms of intensity and position (frequency). For gas samples, this is a technology that is used to monitor emissions from process industry overall the world.

Low emission H_2 production (Task 3)

Modular Protonic Membrane Reformer (PMR) technology for hydrogen production shows great promise with a modeled system energy efficiency higher than 75% with CO_2 capture. PMR technology utilizes electrical energy as input, which becomes an increasing advantage in the transition towards renewable and intermittent energy. In collaboration with CoorsTek Membrane Sciences, our goal is to identify and improve single-tube membranes (6 cm tubular membrane, 1 cm diameter) compatible with modular single engineering units (SEU) up to 0.5 kg H_2/day. The work in NCCS is also aligned with a Gassnova demo project on a semi-integrated PMR prototype and digital-twin at TRL 5.

www.sintef.no/NCCST3

LOW EMISSION H_2 PRODUCTION **(TASK 3)**

PMR experiments at lower temperatures for the first time

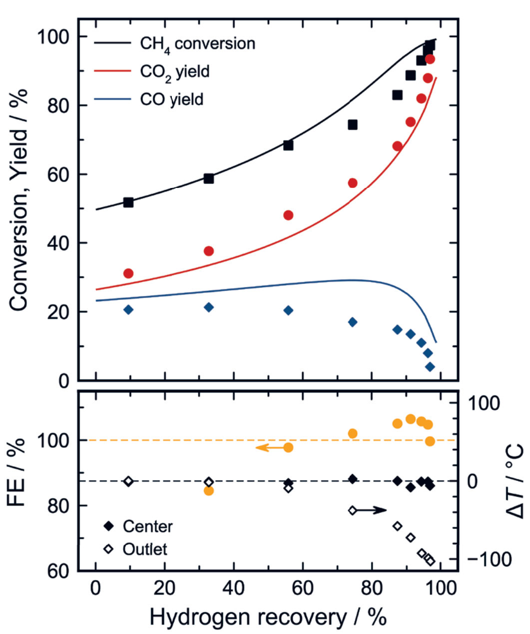
In 2019, we managed to perform catalytic Protonic Membrane Reformer (PMR) experiments at lower temperatures (750 and 700°C) for the first time, for comparison with the standard operation at 800°C (left figure). Methane conversion of 98.7% was achieved and the catalytic data corresponds well with thermodynamic equilibrium at the highest hydrogen recoveries (>95%). These results are important for further optimization of the PMR operating conditions. Specifically, lower operating temperature may translate to improved lifetime and reduced cost of materials and components in the PMR modules.

Improvements to experimental setup

The task-team has made several upgrades to the setup for detailed characterization of PMR membranes. We achieved high quality electrical measurements which provides the main input for further development of membrane cells with improved electrochemical performance. This work also benefits the long-term PMR testing that is planned within KPN MACH-2.

Modelling of membranes and modules

Simulations of PMR membranes and thermally integrated modules are being pursued to benchmark and improve the PMR hydrogen production process. Single-tube PMR simulations were performed for detailed temperature and gas composition profiles along membrane length, and for the role of gas inlet temperature. The results demonstrated the importance of thermal integration of PMR modules, and a simulation framework for a thermally integrated single engineering unit – containing 36 membrane segments – was established for isothermal conditions.



Left: PMR test of single membrane at 700 °C showing CH_4 conversion and CO/CO_2 yield as a function of hydrogen recovery, as well as Faradaic efficiency (FE) and the difference in temperature at the center and outlet of the membrane relative to the process temperature (700 °C).

Right: Module containing 36 membrane segments.

CO_2 capture and transport conditioning through liquefaction (Task 4)

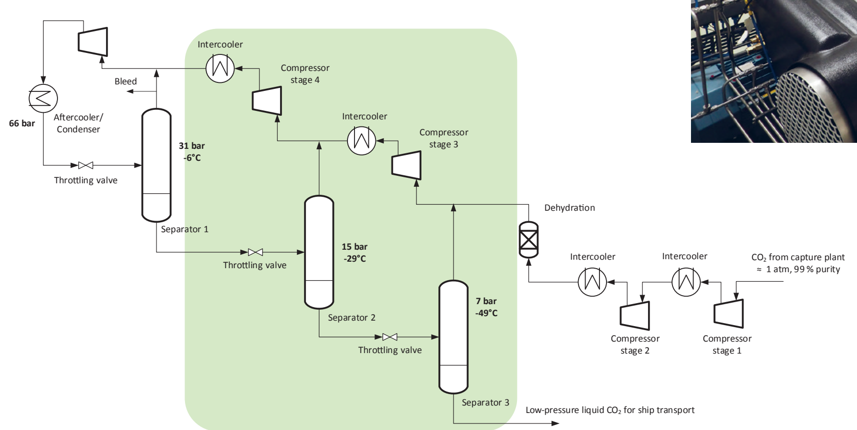
This Tasks looks at the use of liquefaction to optimise transport condition of CO_2, thus making liquification a mandatory processing stage in the interface between capture and transport. To do this, an efficient CO_2 liquefier process will be derived. Energy- and cost-efficiency adhering to transport specifications and safety are important criteria.

www.sintef.no/NCCST4

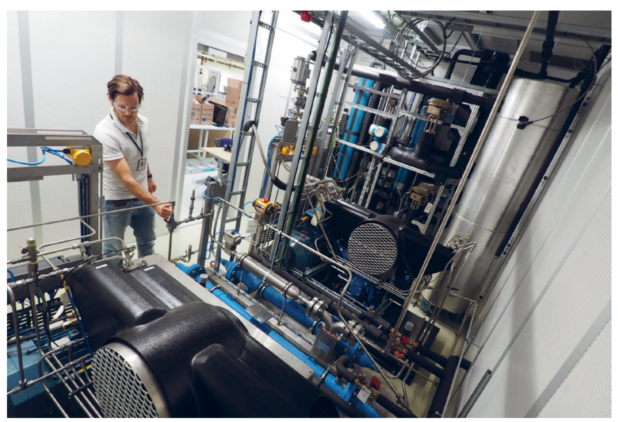
CO_2 CAPTURE AND TRANSPORT CONDITIONING THROUGH LIQUEFACTION **(TASK 4)**

During 2019, we made a theoretical basis for CO_2 liquefaction experiments relevant for full-scale cases for low-pressure transport of liquid CO_2. From this we know how to operate the rig to obtain the desired test conditions, and what to expect in the experiments. An outline of an experimental plan for low-pressure CO_2 liquefaction was also made.

In the MACH2 spinoff project (a spinoff from Task 4) we worked out the necessary upgrades of the CO_2 liquefaction facility to run experiments with flammable and poisonous components, which is required to investigate syngas/retentate separation in hydrogen production. Most of the upgrades were completed in 2019 and January 2020, except some electrical work and implementation of safety systems that has been postponed until after the first NCCS Task 4 experiments are finished. Moreover, an external refrigeration cycle was installed and various upgrades to increase the rigs flexibility and accuracy have been implemented. These upgrades allow us to operate the rig such that we obtain the desired test conditions in both NCCS and MACH2, and increases the accuracy of the results.



Now that the rig is back in operation, several experiments will be conducted. Task 4 will demonstrate the feasible pressures at which liquid CO_2 can be produced and the practical limit with respect to solid CO_2 formation. The experiments will increase the confidence in low-pressure liquid CO_2 transport chains. A lower CO_2 transport pressure has several benefits (e.g. increased liquid CO_2 density, possibility to use larger and lighter tanks, better ship hull utilization) that can reduce the transport costs significantly. In MACH2, the first proof-of-concept for efficient CO_2 separation and purification from H_2-selective membrane retentate gas mixtures is being prepared to pave the way for further development towards an integrated membrane/low-temperature pilot.



Above: The experimental facility.

Left: Liquefaction process diagram showing included parts of the process in the experimental setup relative to an assumed full CO_2 liquefaction process located between capture plant and ship loading terminal.

Gas turbines (Task 5)

Task 5 pertains to combustion in gas turbine engines for power generation and represents the required enabling step that completes the CCS value chain from the Norwegian Continental Shelf and throughout Europe. The overall objective is to assess and improve the stability and operability of gas turbine combustion systems facing issues related to novel and unconventional fuel mixtures. Ultimately, the Task aims to assess the overall impact on power generation, thermodynamic efficiency and pollutants emissions.

www.sintef.no/NCCST5

GAS TURBINES (TASK 5)

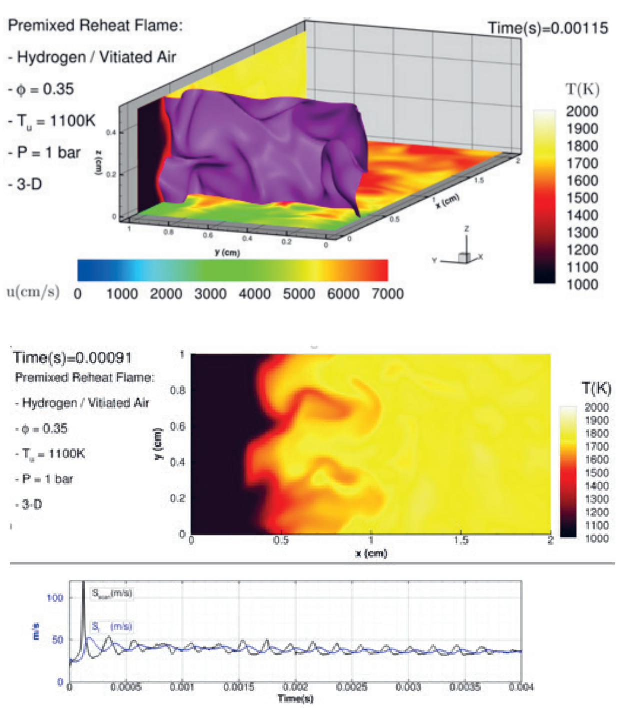
Task 5 research aims to reduce costs related to clean and efficient energy conversion in gas turbines and improve their safety and robustness. In 2019, we made several important steps towards these goals.

In 2019, we have investigated the spontaneous ignition process in hydrogen flames at reheat conditions, with and without inlet forcing utilizing state-of-the-art direct numerical simulations (DNS). Results indicate the occurrence of unsteady ignition and combustion patterns peculiar to hydrogen reheat flames that have not been observed before. Furthermore, results from full-fledged, three-dimensional DNS have provided turbulent flame speed estimates for hydrogen reheat flames (see left figure) spanning a range of turbulence levels and pressure conditions.

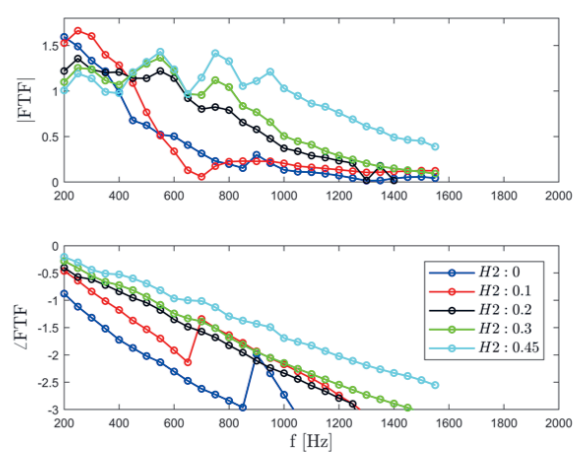
Finally, we have performed measurements of hydrogen/methane premixed flames. Flame Transfer Functions (FTFs) extracted from these measurements revealed a characteristic response pattern not observed earlier (see figure below).

All of this fundamental knowledge is key to assess and improve the robustness of gas turbine combustors operating on pure hydrogen as fuel and will speed up combustor development by OEMs.

NCCS-sponsored KPN "Reheat2H2" was awarded in January, contract work is completed in late spring and project kick-off is arranged on October 23rd (in connection with NCCS CD 2019). The research planned in the KPN Reheat2H2 will optimally complement the ongoing activities of Task 5 and allow special focus to the important issue of combustion dynamics (thermo-acoustic instabilities) in hydrogen reheat flames.



Turbulent flame speed estimates for hydrogen-air mixture at reheat conditions (atmospheric pressure).



Flame Transfer Function -FTF- gain (top) and phase lag (bottom) for different hydrogen content.

CO_2 capture process integration (Task 6)

Task 6 investigates how to best integrate the capture process in the CCS value chain. A generic methodology for post-combustion CO_2 capture in waste-to-energy plants is developed. The methodology will be used to redesign plants so they can support flexibility between heat (steam) and electricity output. The Task will also develop a systematic approach to link solvent properties and cost reduction in end-of-pipe CO_2 capture.

www.sintef.no/NCCST6

CO_2 CAPTURE PROCESS INTEGRATION **(TASK 6)**

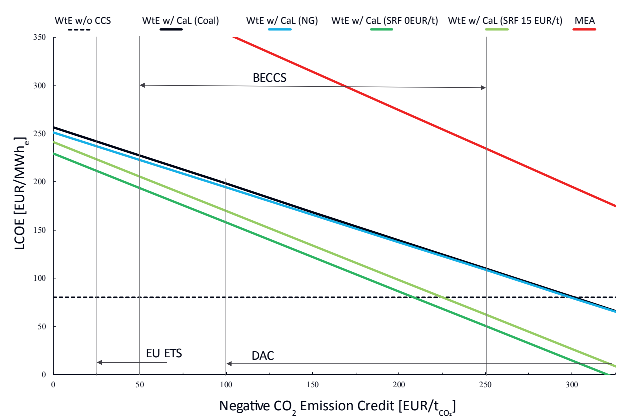
CO_2 capture from Waste-to-Energy (WtE) plants is receiving significant attention due to its potential contribution to negative emissions and its role within the context of sustainable cities.

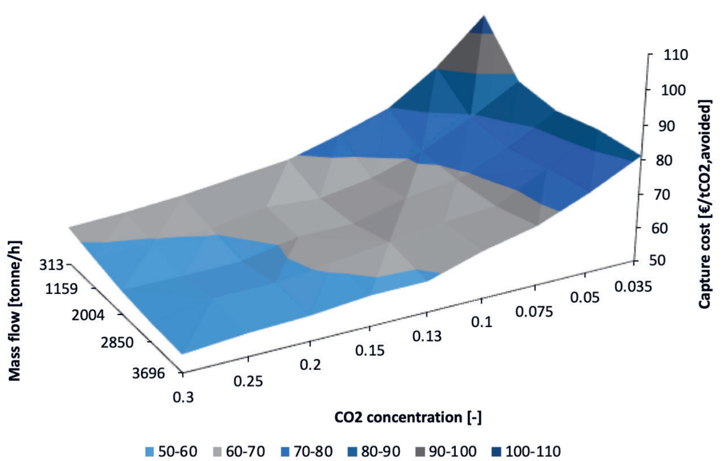
Process integration of Calcium Looping (CaL) in a WtE plant was studied. Results showed the benefit of CaL process compared to different solvents for post-combustion capture for WtE plants, particularly with an emphasis on negative emissions.

Techno-economics of the WtE plant indicate that it is important to consider capture technologies with low energy penalties for capture with trade-off of having much higher CAPEX. While this is generally true of most post-combustion capture applications, it is emphasised in the case of CO_2 capture from WtE plants.

The techno-economic analysis of the WtE plant have provided significant insights on the potential role of WtE plants with CCS being a competitive player in the Negative Emission Technology (NET) arena. This could help drive the business case for CCS in this sector.

Hybrid CO_2 capture technologies can significantly reduce the cost of capture by integrating technologies that are best-in-class within a subset of the overall expected operating range. Pressure Swing Adsorption (PSA) is a suitable technology for bulk removal of CO_2 while the liquefaction process is very good for CO_2 purification. The PSA-Liquefaction hybrid process is a good option compared to PSA process for certain niche applications with sorbents that have high productivity and low selectivity. The identified PSA-Liquefaction process niche has a potential to reduce the cost of post-combustion CO_2 capture using adsorbents.





Above: Levelised cost of electricity of the WtE plant without and with CaL dependent on the CO_2 emission credit.

Left: Impact of scale and CO_2 concentration on cost of CO_2 capture cost using MEA.

CO_2 transport (Task 7)

Captured CO_2 needs to be transported from the points of capture to the storage sites. Task 7 provide knowledge and methods to ensure that the transport is safe and efficient. Running-ductile fractures in CO_2 pipelines, ship transport, and impurities and non-equilibrium flow of CO_2 are investigated.

www.sintef.no/NCCST7

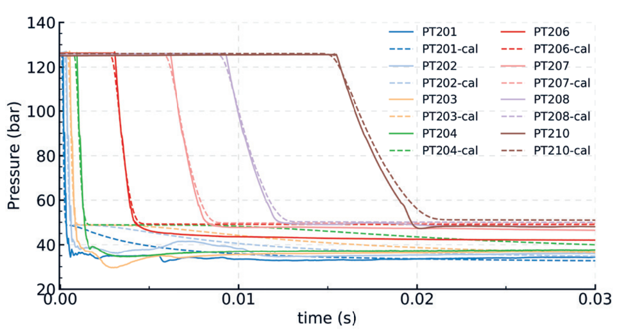
CO_2 TRANSPORT (TASK 7)

ECCSEL depressurization facility and improved models

The ECCSEL depressurization facility became operational in 2019. This facility is specifically instrumented to record fast changes in pressure and temperature as pressure waves propagate in a pipe. These data contribute to safe and efficient CO_2 transport through validation of numerical models which enable us to better design and operate CO_2-transport systems.

Gas and liquid experiments have been conducted with the rig and we obtained preliminary results with high resolution and consistency. The data will be used to validate and improve the fluid part of our coupled fluid-structure (FE-CFD) running-ductile-fracture (RDF) prediction model, as well as models for transient (time-varying) multiphase (gas-liquid and gas-liquid-solid) flow of CO_2 in general. The data will be further analysed and published in 2020.

In addition, we improved our coupled FE-CFD model for predicting running-ductile fracture in CO_2 pipelines by improving our material-model calibration method and by more efficient thermodynamics calculations.



Calculated vs measured pressure as a function of time during depressurization of pure CO_2 from 126 bar, 22 °C. Preliminary but promising results.

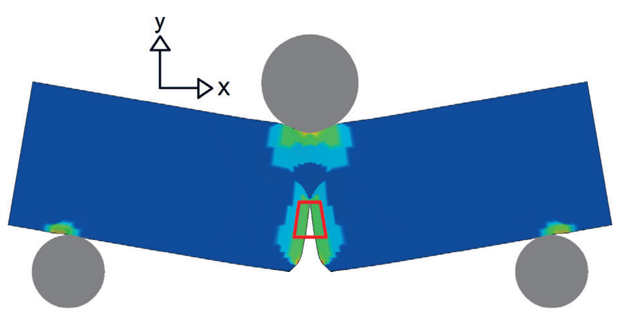
The RDF model can be made available to industry. A way to do this is outlined in the document 'Fracture-propagation-control tool for industry – proposal for a pre-project' submitted to the task family. Putting the model into industrial use could lead to benefits including reduced cost and design margins and lowered project risk.

More efficient simulation of multiphase flow

Our Postdoc at the University of Zurich has developed a new numerical method for compressible ('low-Mach') multiphase flow. This could lead to more efficient simulation tools for multiphase flow of CO_2, that is, simulation tools that can handle a large range of flow situations in a robust and numerically efficient way.

Interest outside of NCCS

A work package on model-based design tools for fracture design and control was part of a bilateral Norway-China application entitled "Digital solutions for predictive maintenance and structural integrity assessment of energy pipelines – Doorstep". This shows that the work attracts interest outside NCCS.



Structure (FE) simulation carried out as part of the material-model calibration study.

Fiscal metering and thermodynamics (Task 8)

Accurate thermophysical properties are needed for optimized design and operation of virtually all processes involved in CCS. This Task aims to provide improved experimental data and models on properties of CO_2-rich fluids relevant for CCS and facilitate fiscal metering of the same fluids.

www.sintef.no/NCCST8

FISCAL METERING AND THERMODYNAMICS **(TASK 8)**

The ImpreCCS KPN project, financed by CLIMIT R&D and the NCCS industry partners, is administered under Task 8. The objectives of ImpreCCS are to produce data on viscosity, density, and thermal conductivity and develop property models which will be applied in reservoir modelling. In addition to the NCCS consortium, NORCE is a research partner in ImpreCCS, and property models are developed in collaboration with NIST, USA.

Measurements of fluid properties and verification and development of thermodynamic models

Equations of state (EOS), used in e.g. all process engineering tools, are normally fitted to experimental data of only binary mixtures. As real-life fluids have multiple components, there is hence a need to verify EOS'es with more complex mixtures at relevant conditions. In CCS, low temperatures are encountered in CO_2 liquefaction, separation, shipping and depressurization, whereas higher temperatures can be encountered in capture, pipeline transport and in reservoirs. Hence, the whole temperature range between the triple (-57°C) and critical point of CO_2 (31°C) is relevant. In 2019, the reference EOS developed in NCCS was compared with new experimental phase equilibria data of the CO_2-N_2-CH_4 system from -50 to 25°C. The deviations were similar to what are found for the binary data to which the EOS has been fitted. Hence, the EOS validity for the important impurities of nitrogen and methane, selected by the NCCS industry consortium, has been confirmed. These findings have been published in Fluid Phase Equilibria.

A revised long-term strategy for property measurements and fiscal metering has been made together with the task family.

A new version of the reference EOS for CCS developed in NCCS, EOS-CG 2019 was released, including description of new components. EOS-CG 2019 is documented through a PhD thesis and two journal papers and made available through the TREND thermodynamic library. Further model developments, including reactive systems and transport properties, are under way.

The new TREND thermodynamic library is directly available for the NCCS industry partners, but the routines of EOS-CG are also expected to eventually find their way to commercial process simulators. The impact is hence global.

EOS-CG 2019, expanded and verified with new ternary measurements in 2019, can now be used for more complex mixtures and with higher confidence thanks to the work of Task 8. Increased confidence of the thermodynamics means less risk in the design and operation of CCS processes, and hence saved costs!

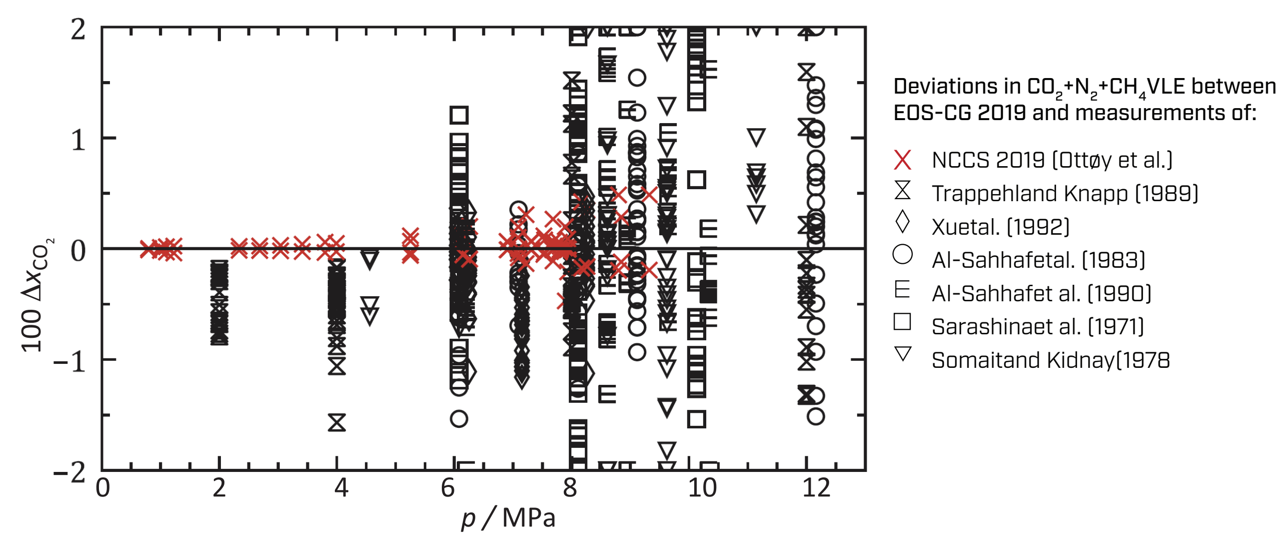
In addition, further measurements and modeling of thermal conductivity, phase equilibria, viscosity, and density were under way or under preparation in 2019 through ImpreCCS, including collaboration and exchange of personnel between SINTEF ER, NTNU, UWA, and NIST.

Fiscal metering

As discussed in the Impacts Study (see page 26), qualified and traceable measurement of mass flow to satisfy public regulations, also called fiscal metering, is a prerequisite for large-scale deployment of CCS. Currently, no technologies have been verified at relevant conditions and flow rates.

Ultrasonic technologies have become a very popular for flow metering of e.g. natural gas, chiefly due to their high accuracy and low pressure drop. However, questions have been raised in the literature concerning their applicability to CCS due the high acoustic attenuation of CO_2. Hence, static testing of an ultrasonic fiscal meter of industrial scale to investigate the impact of acoustic attenuation has been prepared as an activity for 2020. These tests will confirm whether this technology is viable for CCS, which will be a very important result.

As an impact of the work in NCCS, the INFRASTRUKTUR program of the Research Council of Norway funds design of a fiscal metering test loop in 2020. Such a loop will enable verification of different fiscal metering technologies at a relevant industrial scale and at operational and varying conditions. This design will be developed in close collaboration with the NCCS industrial consortium. Without such a test loop, traceable mass flow measurements may not be possible, and CCS systems may be required to purchase emission allowances under the EU emission trading system (ETS). This would be a major blow to CCS profitability.



Deviations between ternary CO_2 + N_2+ CH_4 VLE data and EOS-CG 2019 [1].

1 Ottøy S *et al.* "Thermodynamics of the carbon dioxide plus nitrogen plus methane (CO_2 + N_2 + CH_4) system: Measurements of vapor-liquid equilibrium data at temperatures from 223 to 298 K and verification of EOS-CG-2019 equation of state," *Fluid Phase Equilib.* 2020;**509**:112444.

Structual derisiking (Task 9)

Task 9 focuses on reducing the risks related to the injection and storage of CO_2 on the Norwegian Continental Shelf, with a focus on the geology and faults in the Horda Platform area. Site specific knowledge building for the Smeaheia fault block within the Horda Platform area is combined with observations from field analogies and experimental investigation to address fault seal integrity and develop an improved workflow for dynamic up-along-fault fluid migration.

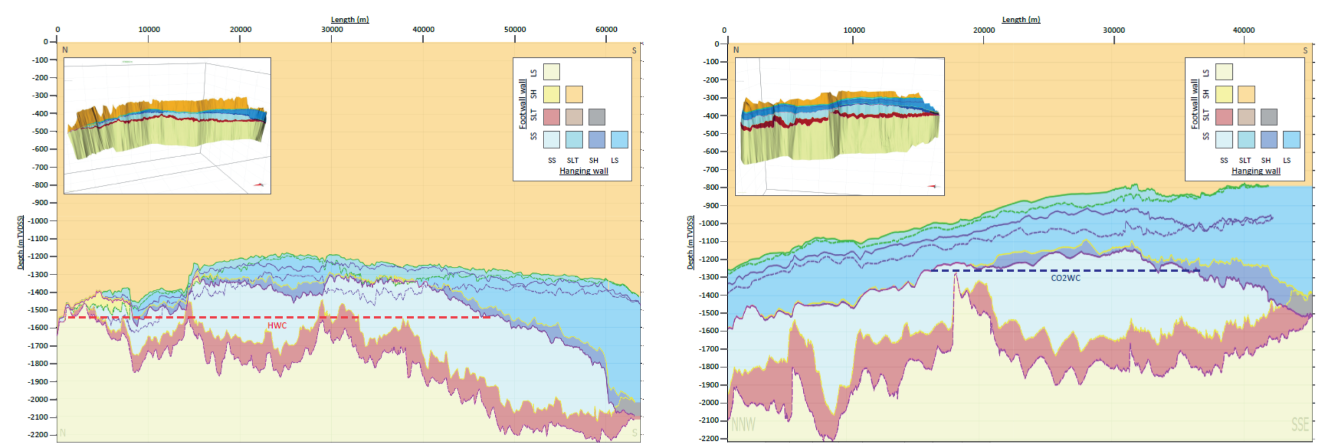
www.sintef.no/NCCST9

STRUCTUAL DERISIKING (TASK 9)

The Horda Platform area is already selected for CO_2 injection within the Northern Lights project. We have therefore conducted a detailed seismic interpretation of two supplementary sites in the same area, the Smeaheia fault block and Triassic Lunde Formation. This has resulted in improved geological understanding of the Horda Platform area, by demonstrating new findings on age relationships, timing and basement involvement for the faults in the area, as well as identifying good reservoir sands in the Triassic.

Our new knowledge on the geology of the Platform has the potential to identify and qualify additional storage volume in this area. More specifically, age relationships and extent of faulting provides important input for the maturation of the area and can help quantify the risk related to fault sealing and reactivation. Identification and qualification of additional reservoir units in areas where storage infrastructure is developed can provide an important step towards large-scale CO_2 storage. Two main uncertainties related to the Horda Platform area, the juxtaposition seal for the Vette fault and the origin of the pockmarks in the overburden have been addressed to further reduce the risk. The seal properties of the Vette fault zone have been demonstrated by comparing the Vette fault with the Tusse fault, a sealing fault within the Troll gas reservoir. The comparison suggests that the geometry and juxtaposition is comparable and similar sealing properties can be expected for Vette fault as for Tusse fault. The most likely source for pockmarks is found to be laterally migrating fluids (from gas chimneys) near the Troll Field, and not from the underlying reservoir-seal system at Smeaheia.

Tusse Fault Zone Lithologic Juxtaposition **Vette Fault Zone Lithologic Juxtaposition**



Illustrating 2019's main results: Across fault juxtaposition modelling comparing Vette and Tusse fault zone. The results show comparable properties indicating that the Vette Fault Zone has similar sealing properties as the Tusse Fault Zone holding the Troll gas column.

CO_2 storage site containment (Task 10)

By ensuring containment of CO_2 in the storage reservoir, we can optimize storage capacity and maximize the number of suitable reservoirs. These goals can only be achieved by addressing remaining research gaps identified in the near-well area (well integrity, CO_2 injectivity) and at reservoir borders with the caprock (especially faults). Task 10 therefore looks at selected issues of relevance for filling these gaps, putting a special emphasis on the understanding of geomechanical aspects and developing testing methodologies to be used in considering new storage sites.

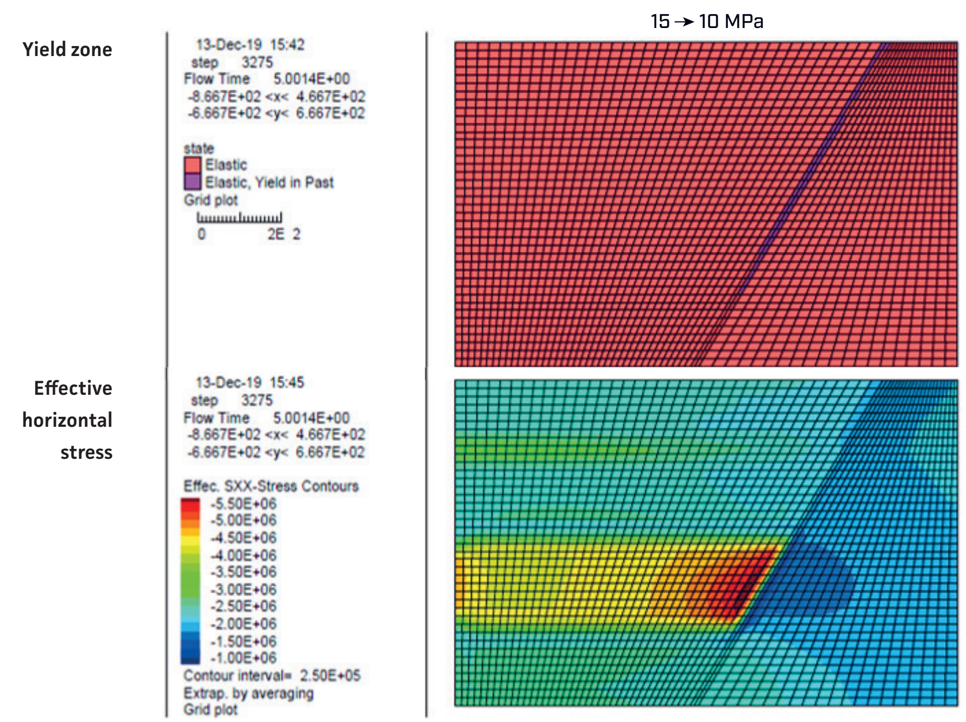
www.sintef.no/NCCST10

CO_2 STORAGE SITE CONTAINMENT **(TASK 10)**

Last year we completed the elaboration of a suggested laboratory methodology to measure the tensile strength of the cement to formation bond. Crucial tests were successfully performed on cement and shale composite plugs, where cement was cured under relevant field conditions.

The bond's tensile strength is the weakest link in maintaining well integrity and this is exacerbated when bonding to shales. This work led to the well-received publication of two peer-reviewed papers, a presentation at the ARMA conference in New York. Many also acknowledged that finally there is a method to measure much needed input parameters for computer simulation work. The methodologies developed in Task 10 will be useful for recommended guidelines when evaluating storage capacity and derisking new considered sites.

In the event of large-scale CCS taking off, this will enable oil and gas or mining service companies equipped with good geomechanics laboratories to offer site survey studies in terms of expected well integrity performance.



New finite element simulations confirming in-house fracturing software results: fault slip towards shallower layers is observed for depletion of reservoir as evidenced by the plastic deformation map (top) with resulting stress distribution map (bottom).

Our collaboration with Lawrence Livermore National Laboratory (LLNL) was strengthened by mutual work on a well integrity problem survey. A detailed questionnaire was sent to all active CO_2 injection operations worldwide. A first round of answers was received and analysed, giving unique insight in which difficulties are most encountered, and where future research efforts are needed. This work will feed into the Well Integrity Atlas, a compilation of well integrity issues encountered at CO_2 storage operations, their severity, mitigation measures and their success. This will be available to all operators, such that learnings can be more readily distributed, but also naturally lead the research community in identifying and addressing remaining gaps.

Together we have proposed new models

We have collaborated closely with Task 9 and the supporting researcher project SPHINCSS. This has led to a series of conceptual numerical models of simple fault and stress conditions whereby permeability along the fault and hence leakage risk from a storage site increases.

The results, where the structure of the fractured zone on each side of the fault core is explicitly modelled using SINTEF's fracturing tool MDEM (modified discrete element method), are surprising as they predict that depleted reservoirs might be more at risk than virgin aquifers, due to stress history effects. The main conclusions have been confirmed using a commercial finite element tool, FLAC by ITASCA (on page 61).

On the basis of this work, we have together with Task 9 proposed new models which address reactivation problems and help us understand specific differences between depleted oil and gas reservoirs and aquifers. This is crucial for gaining confidence in where to invest in CCS and how to scale up operations.

Reservoir management and EOR (Task 11)

Task 11 is developing technologies for optimal utilisation of available storage space, and for efficient utilisation of CO_2 for enhanced oil recovery (CO_2-EOR). Investment both in characterisation of a storage site and in the development of injection facilities (pipelines, well templates and the wells themselves) is costly and needs to be done before injection can start. Therefore, the operator needs to be confident that the storage site can be used to its full potential. Technologies for this are addressed in Task 11's two activities: Mobility control for increased efficiency of CO_2-EOR and aquifer storage, and optimisation of storage site portfolios.

www.sintef.no/NCCST11

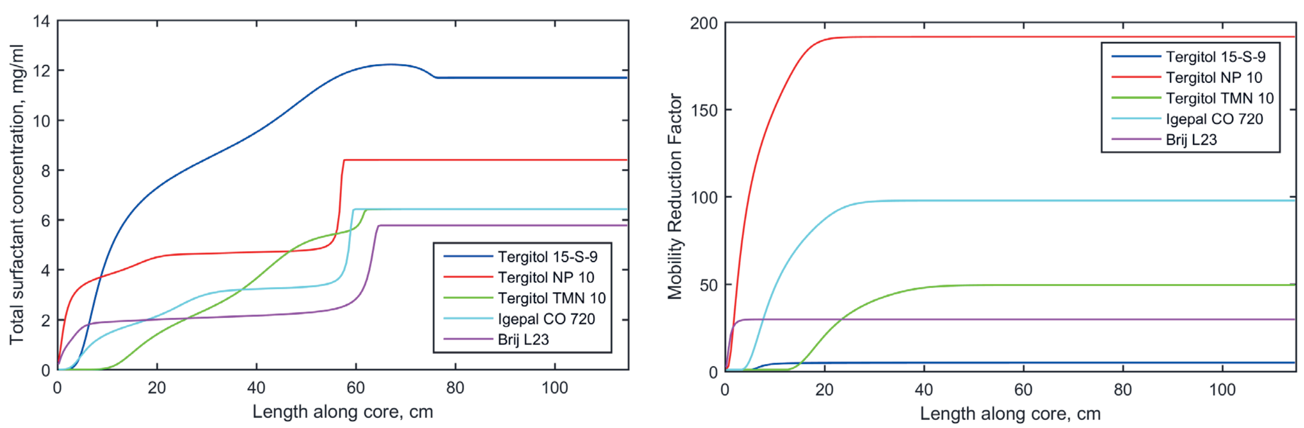
RESERVOIR MANAGEMENT AND EOR **(TASK 11)**

The NCCS CO_2-brine foam module for the MATLAB Reservoir Simulation Toolbox (MRST) has been used to simulate core flooding experiments with different foam-generating surfactants. The results are compared to actual experiments performed with commercially available surfactants. This is valuable information when screening for surfactant properties that will be most beneficial for field application.

Use of foam is a promising method for mobility control of CO_2 in saline aquifer storage. Simulations at field scale indicate that storage capacity can be more than doubled if CO_2 mobility control can be successfully applied in the early phases of the injection operation.

Further delimitation of the scope of a tool for optimisation of storage site portfolios has been discussed with industry partners in workshops. The goal is to aid in the decision-making for the development of CO_2 transport and storage network through the creation of a tool that calculates the incremental cost of reducing the risk of not being able to store an agreed annual/monthly amount of CO_2. The tool will include probabilistic treatment of the unknown geological properties of storage sites.

Robust risk analysis tools for the operation of CO_2 transport and storage networks will enable storage operators to decide the correct level of investment in site characterisation and infrastructure development and the most appropriate timing for the development.



Caption: Results from simulation of core flooding with six different foam-generating surfactants. Pure CO_2 is displacing a solution of formation water and 0.5 weight-% surfactant. The plots show the situation after 0.4 pore volumes have been injected. Differences in CO_2 solubility, adsorption and foam strength between the different surfactants lead to significant differences in the development of total surfactant concentration (including adsorbed surfactant) (left plot) and the mobility reduction effect (right plot). Characterisation of such differences are important when selecting an optimal surfactant for field application.

Cost-effective monitoring technology (Task 12)

Reliable monitoring of a CO_2 storage site is essential for safe and efficient operation, as well as for public acceptance. By carefully monitoring the site before, during, and after CO_2 injection, the risk for very costly intervention, remediation, or site closure, is significantly reduced. Such surveillance can potentially be very expensive. The main ambition of Task 12 is to develop and demonstrate monitoring technology which will enable safe operation in compliance with laws and regulations in the most cost-efficient manner. This is achieved by research on five topics:

- methods for assessment of cost vs value-of-information for geophysical data
- ways of extracting all available information from acquired geophysical data
- strategies for comparing/combining prior reservoir modelling to geophysical observations
- unconventional data acquisition technology and survey layouts
- use of advanced data analytics to handle big data in geophysical monitoring

www.sintef.no/NCCST12

COST-EFFECTIVE MONITORING TECHNOLOGY **(TASK 12)**

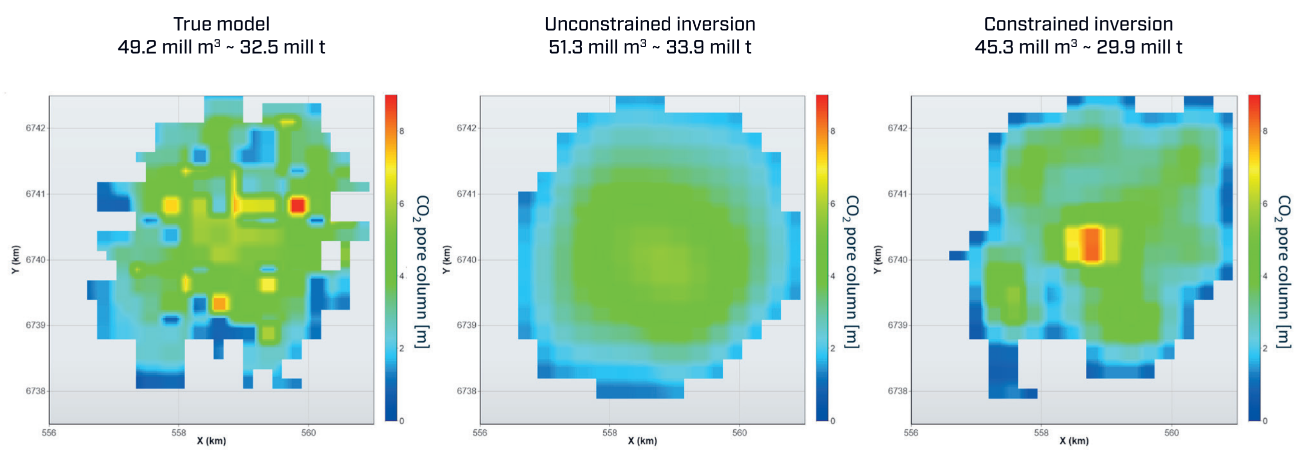
During the year, we applied a newly developed approach for reservoir parameter estimation with uncertainty quantification (Bayesian Rock Physics Inversion) to Sleipner 2008 seismic data. We demonstrated how important reservoir parameters, such as CO_2 saturation and reservoir pressure, can be estimated with a simultaneous assessment of uncertainty, providing essential operational information to the storage site owner. Initial studies also showed how the estimated reservoir parameters can be used to constrain and calibrate reservoir simulations of the Sleipner injection. This calibration enables improved prediction of the future behaviour of the storage site.

The development and testing of a compressive sensing technique for enhanced geophysical data acquisition and interpretation continued in 2019. This technique, which can help to reduce the need for dense (and expensive) seismic surveys, was succesfully verified for sparse subsets of Sleipner data.

Reliable and cost-efficient monitoring will be essential for the Northern Lights project. Task 12 developments like the ones described above will support the design of an optimal monitoring scheme. Another such example is how the research and development of Controlled Source Electro-Magnetics (CSEM), as a complement to seismic, could provide a more cost-efficient and accurate approach for quantitative CO_2 monitoring. Based on synthetic Smeaheia data, a quantitative CSEM inversion study was successfully concluded in 2019 (see figure on page 66). Results show that CSEM can be used to give accurate volume estimates.

For any future storage project, there is also a great value in the research efforts on value-of-information, which offer new ways for an operator to analyse and select optimal geophysical monitoring strategies. During 2019, a conceptual Smeaheia case was used to demonstrate how a novel method for value-of-information analysis, based on machine learning, can be used to determine the optimal way of detecting potential leakage from CO_2 storage.

In 2019, we also initialised two spin-off projects (EM4CO2 and Tophole) for more detailed studies of two important topics. EM4CO2 investigates the use of electro-magnetic methods as a complement to seismic for more quantitative reservoir monitoring information. Tophole studies how the integrity of plugged and abandoned wells can be cost-effectively monitored to enable CO_2 storage in regions with existing wells.



CO_2 volume estimations from CSEM inversion results. Left: True model, Middle: Result with unconstrained inversion, Right: Result with constrained inversion.

RESEARCH RESULTS **IN USE BY PARTNERS**

Task 1:

The activity on optimal ship transport provides valuable knowledge for partners like **TOTAL** and **Equinor** in their development of 7-bar ship technology, to enable cost reductions beyond the first stage in Norwegian full scale and make it cheaper for European industries to send CO_2 to Norway. The new approach to CCS design under uncertainties will improve the functionality of the iCCS tool, which NCCS partners intend to use. The legal activity provides support to address the legal shortcomings to enable ship-based CCS chains.

Task 5:

The results from direct numerical simulations and experiments have revealed distinctive features that significantly differentiate combustion of hydrogen from combustion of methane (natural gas) – this must be taken into account in the design of gas turbine burners. Results from the close cooperation between SINTEF/NTNU and **Ansaldo Energia** are already used to validate simplified (low order) models used by Ansaldo Energia to optimize design and operation of the gas turbine.

Task 7:

Our 'Battelle two-curve method' tool incorporating EOS-CG has been reported to be used by NCCS partners. The SINTEF coupled FE-CFD model for predicting running-ductile fracture in CO_2 pipes was employed by the **Northern Lights project**.

Task 8:

The TREND thermodynamics tool, which is used by the industry for process analyses, came in a new version in 2019. At the request of the industry partners, we made a comparison of measurement data and models for state conditions and mixtures, that are of major importance for ship transport in the **Northern Lights project**. The industry partners have shown great interest in the planning of ultrasonic meter testing. This activity could attract new industrial partners to NCCS.

Task 9:

The Geo model developed by the UiO group for the Johansen Formation (under FME SUCCESS) has been in demand and has been handed over to the **Northern Lights project** in connection with well planning at Aurora. We are experiencing increased interest in Geo models for Smeaheia now that the well at Gladsheim is dry, and we are seeing renewed interest in Smeaheia as a storage area from **Equinor**.

SPIN-OFF PROJECTS

Impact of CO_2 impurities and additives in CCS (IMPRECCS)

The primary objective is to reduce costs and risks of CO_2 storage by predicting the impact of important impurities and additives on CO_2 viscosity, density, and thermal conductivity.

Partners: SINTEF Energy Research, NTNU, NORCE; University of Western Australia
Funding: CLIMIT
Duration: 4 years – Start: 2018
PM: Sigurd W. Løvseth, SINTEF Energy Research

Preventing loss of near-well permeability in CO_2 injection wells (POREPAC)

POREPAC will obtain data and models on near-well processes affecting injectivity that can be used by the industry to better predict and mitigate injectivity issues.

Partners: SINTEF Industry, SINTEF Digital, UiO, IRIS
Funding: CLIMIT
Duration: 4 years – Start: 2018
PM: Malin Torsæter, SINTEF Industry

Membrane-assisted CO_2 capture through liquefaction for clean H_2 production (MACH-2)

The MACH-2 project will develop and demonstrate the potential of an innovative hybrid technology for H_2 production with CO_2 capture enabling high carbon capture rates with high purity CO_2 and H_2 and a hydrogen cost comparable to conventional technologies without capture.

Partners: SINTEF Industry, SINTEF Energy Research, NTNU and West Virginia University. CoorsTek has an active role in the project.
Funding: CLIMIT
Duration: 3 years – Start: 2019
PM: Thijs Peters, SINTEF Industry

Quantification of fault-related leakage risk (FRISK)

The main goal is to reduce the uncertainty in fault-related leakage risk for large-scale CO_2 storage by developing an improved fault derisking framework that includes dynamic pressure changes and along-fault fluid migration.

Partners: NGI, UiO, NORCE (Uni Research) and UiB. Collaboration with UK and US research institutions and geological expertise from Switzerland.
Funding: CLIMIT, Equinor and TOTAL.
Duration: 3 years – Start: 2019
PM: Elin Skurtveit, NGI

Accelerating CSEM technology for efficient and quantitative CO_2 monitoring (EM4CO2)

The primary objective of this project is to develop and apply a cost-efficient CO_2 monitoring concept using time-lapse CSEM and demonstrate its readiness for the future Norwegian large-scale CO_2 storage project (Smeaheia/Johansen).

Partners: SINTEF Industry, NGI, UiO, University of Southampton and collaboration with several other international research institutions on the open-source CSEM software. EMGS will be an advisor in the project and will host the PhD for parts of the employment.
Funding: CLIMIT
Duration: 3 years – Start: 2019
PM: Anouar Romdhane, SINTEF Industry

Tophole monitoring of permanently plugged wells

The primary objective of the project is to develop a novel cost-efficient method for tophole/non-invasive monitoring of permanently plugged wells that are cut below surface/seafloor.

Partners: SINTEF Industry, SINTEF Digital, NTNU, Lawrence Livermore National Laboratory. Aker Solution will have an active role in the project.
Funding: Petromaks2
Duration: 4 years – Start: 2019
PM: Cathrine Ringstad, SINTEF Industry

Towards clean and stable hydrogen reheat combustion in gas turbines (Reheat2H2)

The primary objective is to build a knowledge-based stability model for H_2 reheat flames to enable hydrogen end-use for largescale power generation in pre-combustion CCS (CLIMIT scope) and power-to-H_2-to-power (ENERGIX scope) schemes.

Partners: SINTEF Energy Research, NTNU, TUM, Sandia National Laboratories, Computational Thermal Fluids Laboratory of the University of Connecticut, ETH Zürich. The project will work closely with Ansaldo Energia Switzerland.
Funding: EnergyX
Duration: 4 years – Start 2019
PM: Jonas Moeck, NTNU

INTERNATIONAL COOPERATION

Strategic activities in Europe

Active participation in organisations spearheading strategic CCS development across Europe is a priority for NCCS.

In this way, NCCS and Norway can contribute to the agenda-setting of CCS.

Dr. Nils Røkke (Chair of the NCCS Special Advisory Group and the Centre Assembly) is the current Chair of the **European Energy Research Alliance** (EERA). With 175 research centre and university members from 27 countries, EERA's objective is to build on national and EU research initiatives and to be the cornerstone in the European Strategic Energy Technology Plan. The CCS Joint Programme under the EERA (EERA JPCCS) is an authority on CCS RD&I.

Dr. Nils A. Røkke, Executive Vice President Sustainability, SINTEF.

The **CCS-JP** provides strategic leadership to its partners and coordinates national and European RD&I programs to maximize synergies, facilitate knowledge sharing and deliver economies of scale to accelerate the development of CCS. Dr. Marie Bysveen has held the coordinator role in JP-CCS since 2015.

Dr. Marie Bysveen, Chief Marketing Director, SINTEF Energy Research.

Since 2010, Dr. Nils A. Røkke has been co-chair of the **European Technology Platform for Zero Emission Fossil Fuel Power Plants** (ZEP). ZEP is a coalition of stakeholders united in their support for CO_2 capture and storage as a key technology for combating climate change. ZEP serves as advisor to the EU Commission on the research, demonstration and deployment of CCS. Focus on improving the CCS funding situation in the recently-released FP9 (Horizon Europe) program will continue in 2020.

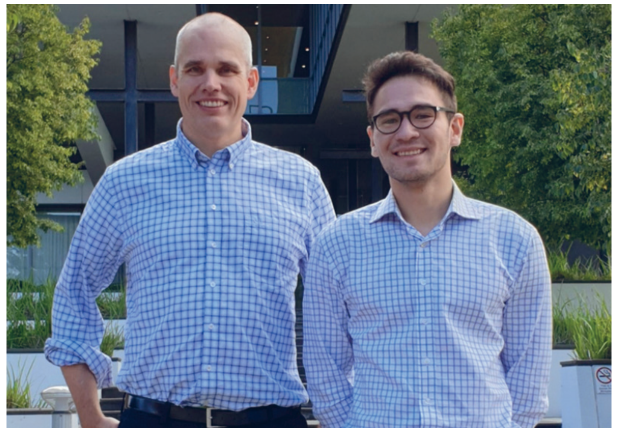
NCCS interacts with the US National Energy Technology Laboratory (NETL), and the UK CCS Research Centre (UKCCSRC). The NCCS Centre Director has a seat in the UKCCSRC Board.

NCCS Mobility Program

Researcher mobility can be a catalyst for innovation, networking, knowledge sharing, and dissemination between research institutions and partners that cannot be done as efficiently remotely. In 2019, NCCS launched a dedicated mobility program to facilitate these activities.

In total, NCCS has awarded eight mobility grants, of which four have been completed in 2019. Blogposts about the research stays are available on the SINTEF Energy Blog.

Thermal Conductivity in CCS
– New measurement data in unchartered territory
In the first call for proposals in late 2018, Task 8: Thermodynamics and Fiscal and its leader, Senior Research Scientist Sigurd W. Løvseth, was awarded funding for a research stay at the University of Western Australia (UWA) for seven months in 2019 to work on closing the knowledge gap on thermal conductivity. We are also grateful for complementary funding from the CLIMIT programme. A full blogpost can be found at: https://blog.sintef.com/sintefenergy/ccs/thermal-conductivity-ccs/



Sigurd W. Løvseth of SINTEF Energy Research and Martin Khamphasith of UWA outside the ARRC research facility in Perth. Martin has since had an exchange at SINTEF in Trondheim.

Utilization of Municipal Solid Waste to Achieve Negative CO_2 Emissions
Martin Haaf, Research Scientist at the Institute for Energy Systems & Technology (EST) at Technische Universität Darmstadt (Germany), had a three month stay at SINTEF Energy Research. Martin studied fluidized bed-based CCS processes, with particular interest in calcium looping technology. His background and research motivation complimented the content of NCCS Task 6, which partly focuses on CO_2 capture process integration into Waste-to-Energy (WtE) plants. A paper, "Impact of Uncertainties on the Design and Cost of CCS From a Waste-to-Energy Plant" was published with NCCS researchers and Martin as a result of his mobility grant.

Read the full blogpost here:
https://blog.sintef.com/sintefenergy/ccs/municipal-solid-waste-negative-co2-emissions/

Oxidative degradation of CO_2 capture
Vanja Buvik, PhD student from NTNU working in Task 2: Solvent technology – environmental effects, spent a month in Delft at TNO studying oxidative degradation in CO_2 capture.

From her NCCS Mobility Travel blogpost:

"The problem that we are trying to solve, is something that is important for both economy and environment. Oxidative degradation of the chemicals used for CO_2 capture is very problematic and for the time being difficult to control. Imagine a bruised apple, which has turned brown because of oxidation. You can't get your fresh red apple back and are left with the choice between eating a less tasty apple or buying a new one.

The concept is similar for carbon capture with chemical solvents; either you have a less efficient process, or you have to buy new solvent. We can even add another aspect to it; if the apple gone bad makes you sick you can compare that to the damage degraded solvents can cause on the equipment!

Since we know that oxygen plays a role in this process, we are trying to find out exactly what role this is, so we can find solutions to solve or avoid this problem. If we can, it could make the currently good technology even better and more robust.

TNO built a setup for studying oxygen solubility in different solutions, and as soon as I received the "all clear" on my mobility funding, I packed my dissolved oxygen sensor and voyaged south. For a month we ran experiments day and night, making progress faster than we had done until then in our separate labs, when it comes to understanding the concept of oxygen presence and how fast oxygen is "eaten" or consumed by the chemical solution. The results from these experiments have already proven relevant both for the fundamental research as well as for the further development of oxygen removal techniques and has given both us at NTNU and TNO the taste for more close collaboration in the future.

Thank you for a month of valuable research and knowledge exchange TNO, and tank you Netherlands for the stroopwaffels! I'm sure this is not the last I've seen of the cute city of Delft, my new favourite chocolate café or TNO.

If you want to hear more about my research, you can read "Finding the perfect solvent to capture CO_2, available here: https://www.ntnutechzone.no/en/2019/07/finding-the-perfect-solvent-to-capture-co2/

Read the full blogpost here: https://blog.sintef.com/sintefenergy/ccs/oxidative-degradation-co2-capture-nccs-mobility-fund/

Multiphase CO_2 flow: New numerical method
Barbara Re, Postdoctoral fellow in Task 7 from University of Zurich, spent five weeks in Trondheim developing a new numerical method for multiphase CO_2 flows.

During her stay at SINTEF, the team collaborated to include an accurate thermodynamic model that can describe the behavior of both liquid and gas carbon dioxide. They implemented this model into the simulation software that we have developed in Zürich, and now we are able to compare its capabilities, especially in terms of robustness and computational time, with existing simulation tools.

Read the full blogpost here: https://blog.sintef.com/sintefenergy/multiphase-co2-flow-nccs-mobility/

Barbara Re, while enjoying some leisure time in Trondheim.

Horizon 2020 - ongoing projects:

- **Pre-ACT - *Pressure control and conformance management for safe and Efficient CO_2 storage - Accelerating CCS technologies.***
  Partners: SINTEF, NORSAR, BGS, PML, GFZ, TNO, Equinor, Total, Shell, TAQA. [**Task 11**].

- **ALIGN-CCUS** - ***Accelerating low-carbon industrial growth through CCUS.***
  Partners: Asahi Kasei Europe, Bellona, British Geological Survey, CO_2 Club Association, ECN, FEV, Forschungszentrum Jülich, GeoEcoMar, Heriot-Watt Univ., IFE, Imperial College London, Leiden Univ., Mitsubishi Hitachi Power Systems Europe, Norcem, NTNU, NUSPA, PicOil, RWE Power, RWTH Aachen Univ., Scottish Enterprise, SINTEF, TAQA Energy, TCM, Tees Valley Combined Authority, TNO, UK Pilot-scale Advanced Capture Technology Facilities-PACT, Univ. of Edinburgh, Univ. of Groningen, and Yara. [**Task 11**].

- **Elegancy** – ***Enabling a low-carbon economy via hydrogen and CCS.***
  Partners: SINTEF, BGS, PSI, TNO, Swerea MEFOS, ETH Zurich, Imperial College London, Ruhr Universität Bochum, Utrecht University, UiO, Aker Solutions, Gassco, Equinor, INEOS, Climeworks, Open Grid Europe, Uniper, Gerg, Scottish Enterprise, Sustainable Decisions, First Climate, TOTAL. [**Task 7, Task 1**].

Horizon 2020 - applications:

- **ACCESS – *Providing European access routes to the North-Sea CCS cluster.*** Partners: SINTEF Energi, Equinor Energy, Norcem, Saipem, VDZ, Moss Maritime, EEW Energy from Waste, Politecnico di Milano, A2A Ambiente, Eidgenoessische Technische Hochschule Zuerich, Fortum Oslo Varme, Heidelberg-Cement, Zweckverband für die Kehrichtbeseitigung im Linthgebiet, ITEA, Forschungszentrum Jülich, Jura Management, CIAOTECH PNO, Perspectives Climate Research, and Linde Aktiengesellschaft. Application sent September 2019 [**Task 1, Task 6, Task 8**].
- **STEP – *Storage of electric power for load levelling in the European energy system.*** Application sent August 2019. Includes R&D for large-scale energy storage. Partners: Ansaldo Energia, EdF, Linde, Artelys, CERFACS, Universita' di Genova, and SINTEF [**Task 5**].

Other applications:

- **CAVALIER – *Novel Methods for Carbon Dioxide Mixture Vapour Liquid Equilibria Measurements.*** Application sent to Polish Grieg program financed by Norway Grants. Builds on VLE activity [**Task 8**].
- **ECOCHINO – *Technology and demonstration of combined cooling, heating and power based on photovoltaic-solar thermal-energy storage-heat pump composite system.*** Application sent to bilateral program for energy research Norway-China. Includes phase equilibria measurements [**Task 8**].

Strategic cooperation with other countries:

Canada
Cooperation with University of Alberta is initiated with focus on reducing costs for low carbon hydrogen production based on adsorption-based CO_2 capture technologies [**Task 1**].

China
Application sent to bilateral program for energy research Norway-China, includes phase equilibria measurements. Title: *Technology and demonstration of combined cooling, heating and power based on photo-voltaic-solar thermal-energy storage-heat pump composite system* – ECOCHINO [**Task 8**].

South-Africa
INTPART application titled "*CO2EduNet – The Norway – United States – South Africa Network for Research based CCS Education*" was developed as a cooperation with South-Africa. Partners were: University of Oslo, NTNU, SINTEF, The NETL lead Carbon Capture Simulation for Industry Impact consortium (CCSI2): Carnegie Mellon University, SACCCS/University of Pretoria. The application was not granted [**Task 9**].

USA
- **Sandia NL** at Combustion Research Facility, Livermore, CA is a very active research partner contributing to hydrogen combustion activities [**Task 5**].
- One publication is written as a cooperation between Ruhr Universität Bochum and **NIST** (USA). Title: *Fundamental Thermodynamic Models for Mixtures Containing Ammonia*. Sent to Fluid Phase Equilibria [**Task 8**].
- Cooperation with University of Texas Austin and their projects in the Gulf of Mexico is established under the new spin-off project FRISK. PhD student Johnathon Osmond has received a NCCS mobility stipend og will visit Austin for some months during 2020 [**Task 9**].
- Fruitful cooperation with Jaisree Iyer from Lawrence Livermore and Greg Lackey from National Energy Technology Laboratory about the Well Integrity Atlas. LLNL is partner in NCCS and NETL has obtained additional funding from Department of Energy [**Task 10**].

- Cooperation with Lawrence Livermore National Labs on monitoring of well integrity (via TOPHOLE) [**Task 12**].

Other countries:

- The new approach for design of CCS value chains under uncertainties is used in a cooperation with a PhD candidate from Technische Universität Darmstadt (**Germany**), [**Task 1**].
- PhD candidate from NTNU has, via the NCCS mobility program, spent one month at TNO (**Netherlands**) working with oxygen solubility [**Task 2**].
- Cooperation with TU Munich (**Germany**) under the KPN project "Reheat2H2". TUM contributes with a unique experimental setup [**Task 5**].
- NCCS was host for PhD student from TU Darmstadt (**Germany**). Cooperation on integration of energy recovery plant with CaL for CO_2 capture. The student stayed at SINTEF from March to June 2019, og the cooperation continued throughout the year producing a joint publication (submitted for publishing) [**Task 6**].
- A Postdoc from University of Zürich (**Switzerland**) working on development of highly accurate numerical methods for multiphase flow of CO_2, had a research period at SINTEF. The cooperation aimed at integrating the CO_2 thermodynamic into the method [**Task 7**].
- We have an extensive cooperation with Ruhr Univ. Bochum (**Germany**). This is related to a CO_2-N_2-CH_4 paper for publishing and other development activities [**Task 8**].
- A PhD candidate from University of Western Australia (**Australia**) astayed at SINTEF for the period August to December [**Task 8**].
- Cooperation with the Mont Terri laboratory (**Switzerland**) og Herriot Watt University in Edinburgh (**Scotland**) is established under the FRISK KPN project. PhD student Peter Betlem had a short research stay in **Netherlands** where he spent time with Shell's DETECT project og Vrije Universiteit Amsterdam [**Task 9**].
- Cooperation with University of Southampton (**Great Britain**) under EM4CO2 with the aim of developing electromagnetic methods for CO_2 monitoring [**Task 12**].
- Cooperation with BGS (**Great Britain**), which contributes in analysis methods for seismic data. Annual budget is 1 MNOK [**Task 12**].

Norwegian tender to host GHGT-16 in 2022

In September 2019, NCCS filed a tender to the IEA Greenhouse Gas R&D Programme (IEAGHG) for Norway to be the host of the GHGT-16 Conference in 2022.

With 1000-1500 delegates, GHGT is the biggest conference dealing with CCS. The conference is staged every second year in one of the programme's member countries and rotates between Asia/Oceania, Europe and America. The next conference, GHGT-15, will be organised in Abu Dhabi, UAE in fall 2020, while the GHGT-16 will come back to Europe.

The Norwegian tender, which was presented by Dr. Nils Røkke to the IEAGHG Executive Committee at its fall meeting in Houston, TX, promised the "greenest GHGT ever". To be held at the newly renovated an expanded Trondheim Spectrum in the city centre of Trondheim, most everything would take place within walking distance, with minimal requirements for transportation.

Proposed venue for GHGT-16, Trondheim Spektrum.

Special efforts will be made to leave a minimal environmental footprint, with short-travelled food and minimal waste (food, paper plastics, etc.). The timing of the conference according to the tender is June 26 – July 1.

The decision about where GHGT-16 will be held will be announced at the GHGT-15 conference (October 5-8, 2020). Trondheim also staged the GHGT-8 conference in 2006.

2019 - Mission Innovation workshop

A Mission Innovation CCUS Workshop Experts' workshop was held in Trondheim, Norway on June 19-20, 2019, with 135 attendees from around the world.

The purpose was to continue the work from the Houston workshop (September 2017) towards implementation and commercialization of CCUS technologies. The objective was to contribute in transferring early (low TRL) research activities to development and innovation activities (higher TRL) by developing recommended paths for emerging CCUS technologies and suggestions for new and joint activities. While the Houston workshop focused on early stage research in CCUS, this workshop focused on strengthening collaboration between industry sectors and research institutions, and public and private sector, by identifying RD&I gaps of common interest.

The workshop addressed six topics; 1) Decarbonizing industry sectors, 2) The role of CCS in enabling clean hydrogen, 3) Storage and CO_2 networks, 4) Storage monitoring, 5) Going climate positive, and 6) CO_2 utilization. During group work sessions, the following questions were addressed: 1) Which opportunities are identified from an industrial point of view?

2) How do we most effectively get from research to commercial product?, and 3) What joint activities could be established to accelerate technology development and implementation?

The final report from the workshop contains an executive summary with short-, medium- and long-term recommendations to accelerate CCUS implementation as related to the topics addressed, as well as topical summaries. The appendix section of the report contains the introductory presentations and group work presentations.

The workshop was organised and co-hosted by Brian Allison (BEIS, UK) representing Mission Innovation Challenge CCUS and Dr. Nils A. Røkke (Executive Vice President Sustainability) SINTEF. Sponsors of the workshop were The Norwegian Research Council, CLIMIT, TOTAL, Equinor ASA, Gassnova SF, SINTEF Energy Research, Department for Business, Energy & Industrial (UK), and The Norwegian CCS Research Centre.

The final report can be downloaded here: https://www.sintef.no/en/events/mission-innovation-ccus-workshop/

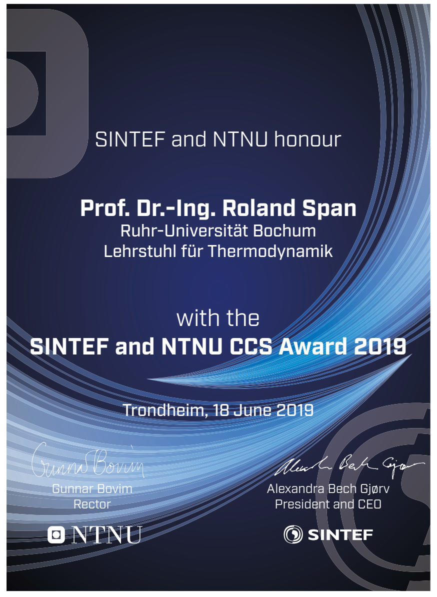
AWARDS AND RECOGNITIONS

Awards

Professor Roland Span was given the *SINTEF and NTNU CCS Award* 2019 at the TCCS-10 Conference.

The award honours his extraordinary contributions and outstanding work in the field of carbon capture technologies. He is especially recognized for his dedication and active commitment to international co-operation within the field of transport and thermophysical properties of CO_2. He has worked tirelessly with lowering the costs and reducing the risks of large-scale deployment of CCS systems.

Nils A. Røkke, SINTEF, Roland Span, RUB and Johan Hustad NTNU Energy.



SINTEF and NTNU CCS Award.

Read more about the award and watch and the interview Professor Span gave just after receiving it in this blogpost on the SINTEF Blog:

https://blog.sintef.com/uncategorized-en/professor-roland-span-won-the-sintef-and-ntnu-ccs-award-2019-at-tccs-10/

Keynote lectures:

Bastien Dupuy was invited to give a keynote talk at the SEG Postconvention Workshop on "Long term monitoring of CO_2 geosequestration: continuous surveillance and quantitative interpretation" in San Antonio (USA), 2019. The title of the talk was: "Quantitative monitoring and uncertainties during multiphysics inversion" (Dupuy B., Romdhane A. and Eliasson P.).

Invited assignments:

Simon Roussanaly was invited to give a presentation at the IEAGHG cost network 2019 workshop to give a presentation on "Methodological costing issues for CCS from industry", the proceeding of the workshop are available at: https://ieaghg.org/ccs-resources/blog/new-ieaghg-technical-report-2019-06-proceedings-ccs-cost-network-2019-workshop.

Rahul Anantharaman was invited by the EU financed project ENERGY-X to participate in an international workshop panel. The objective was to produce a "white paper" about the need for research within CO_2 capture. The report is available at: https://www.energy-x.eu/research-needs-report/ (Chapter 10).

Svend Tollak Munkejord was invited to give a full one-hour presentation of our work on CO_2 transport and safety at "CO_2-lagringsforum" at the Norwegian Petroleum Directorate, March 12, 2019. Also, he and Mari Voldsund are members of the committee "ISO TC/265 Carbon dioxide capture, transportation and geological storage".

Task 9 was invited to present their fault risk work in the "NPD CO_2 lagringsforum", May 28, 2019. Elin Skurtveit gave the presentation. Elin was also invited to share new knowledge on fault and fractures from ongoing laboratory work at the PRE-ACT stakeholder meeting in Brussel, Oct 10, 2019. Further, she was invited to talk about CCS in Norway and research collaborations at the UiO Energy Forum 2019.

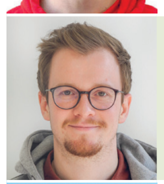
NCCS also received an invitation to contribute to a book chapter to AGU/Wiley's book on CO_2 monitoring in 2018: "Towards quantitative CO_2 monitoring: A case study at Sleipner" (A. Romdhane, B. Dupuy, E. Querendez, and P. Eliasson). The book is to be published.

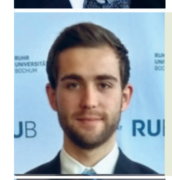
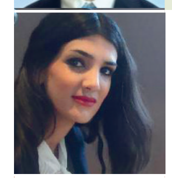
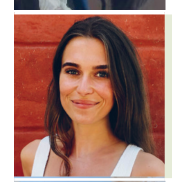
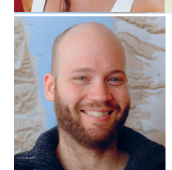
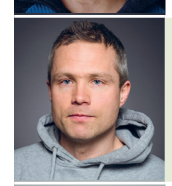
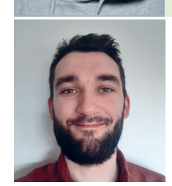
RECRUITMENT

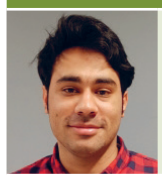
Postdoctoral researchers working on projects in the Centre with financial support from other sources

	Name	Nationality	Period	Sex	Topic	Task	Source
	Donghoi Kim	South Korea	07/2019 - 06/2021	M	Modeling of hybrid processes (H_2 production and CO_2 liquefaction)	3	KPN: Mach-2
	Emma Michie Haines	UK	02/2020 - 07/2022	F	Structural geology	9	KPN: FRISK

PhD students with financial support from the Centre budget

	Name	Nationality	Period	Sex	Topic	Task
	Vanja Buvik	Norway	10/2017 - 08/2021	F	Effect of amine structure on solvent stability of CO_2 absorbents	2
	Lucas Braakhuis	Nether-lands	10/2019 - 10/2022	M	Modelling solvent degradation and reclamation in amine-based post-combustion carbon capture	2
	Stefan Herrig	Germany	06/2017 - 07/2018	M	New Helmholtz-energy models for pure fluids and CCS-relevant mixtures	8
	Jonathon Osmond	USA	10/2017 - 09/2021	M	3D structural characterization and containment risk analysis of two CO_2 storage prospects in the Smeaheia area of the Northern Horda Platform, Norwegian North Sea	9

	Name	Nationality	Period	Sex	Topic	Task
	Vegard Bjerketvedt	Norway	10/2017 - 10/2020	M	Optimal design and operation of CCS value chains with focus on the transport system	1
	Eirik Æsøy	Norway	03/2018 - 03/2022	M	Experimental investigations into forced and self-excited azimuthal combustion dynamics modes	5
	Tobias Neumann	Germany	01/2017 - 12/2021	M	Improved description of minor components relevant for the transport of CO_2-rich mixtures including chemically reacting systems	8
	Bahereh Khosravi	Iran	12/2018 - 11/2021	F	Viscosity and density measurements of CO_2 and CO_2-rich mixtures at conditions relevant for CCS	8
	Camilla Louise Würtzen	Denmark	09/2018 - 09/2021	F	Tectonostratigraphic analysis of CO_2 storage reservoirs in the Upper Triassic alluvial Lunde Formation in the Smeaheia area, Norwegian North Sea	9
	Peter Betlem	Nether-lands	03/2019 - 03/2023	M	Geological and geophysical analysis of overburden for CO_2 storage sites	9
	Magnus Soldal	Norway	06/2019 - 05/2022	M	Fault geomechanics	9
	Marcin Duda	Poland	01/2018 - 12/2020	M	Overburden pore pressure changes due to fluid injection	10

	Name	Nationality	Period	Sex	Topic	Task
	Mohammad Masoudi	Iran	09/2018 - 08/2021	M	Modeling nucleation reactions	10

PhD students working on projects in the Centre with financial support from other sources

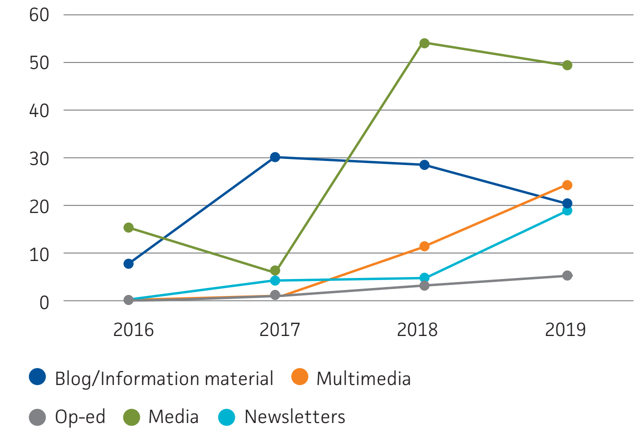
	Name	Funding	Nationality	Period	Sex	Topic	Task
	Mats Rongved	KPN project	Norway	08/2015 - 03/2018	M	Hydraulic fracturing for enhanced geothermal systems	10
	Dongchan Kim	Inter-national	Korea	08/2019 - 04/2020	M	Measurements of thermal conductivity	8

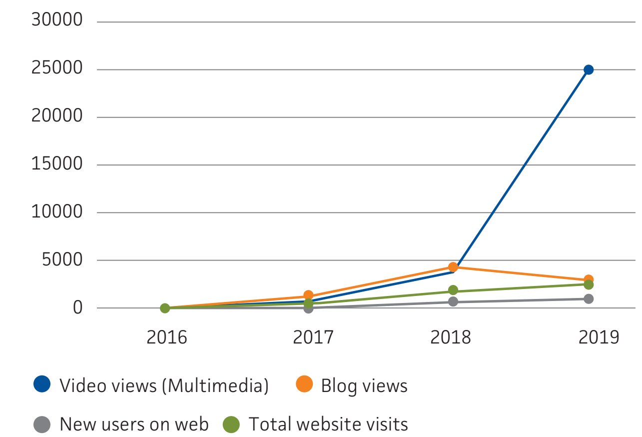
COMMUNICATION

Communicating results to partners as well as non-NCCS participants is a vital activity. The main platform for communicating results to the outside world is the website (www.nccs.no), where all open results are published. In 2019, we continued sending newsletters at least every two months and our well-received webinar series for the partners. Great emphasis is placed on encouraging researchers to produce blogs about their results and activities.

Reaching NCCS' vision of fast-tracking CCS deployment requires sharing knowledge and findings within the CCS scientific community, industrial and political willingness, as well as public acceptance. Communication from the Norwegian CCS Research Centre is therefore an important strategic activity in order to reach the Centre's goals.

NCCS' communication aims to extend communication beyond the NCCS consortium and scientific community to provide facts to the public CCS debate, promote innovations to industry and help increase public support for CCS.

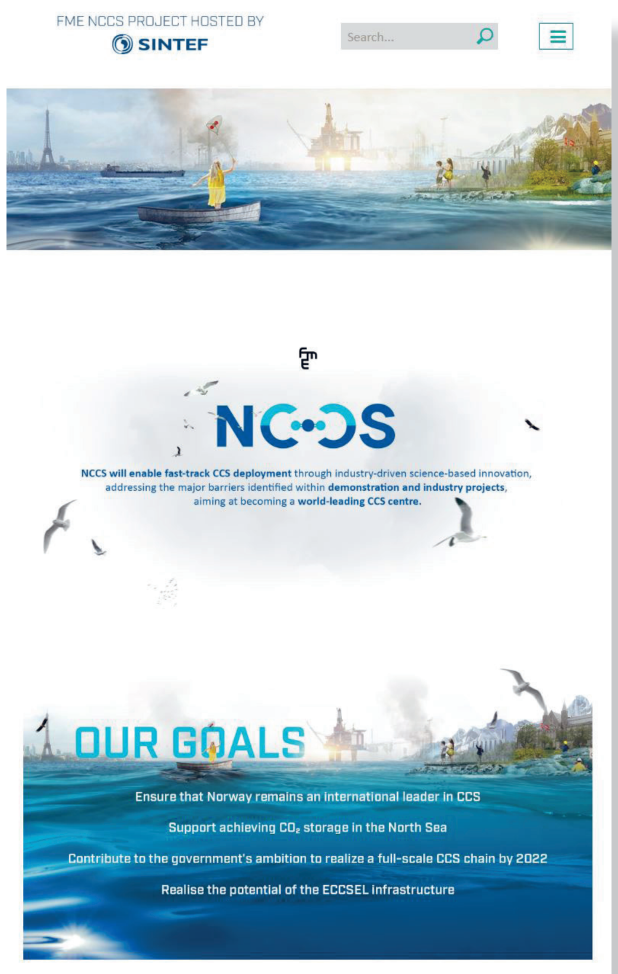




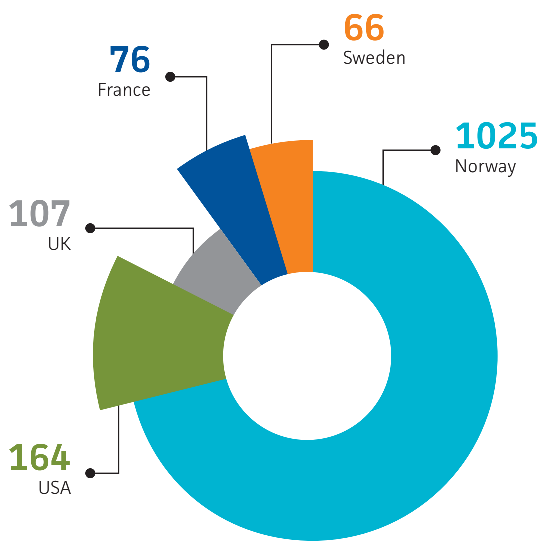
Communication Channels

Web

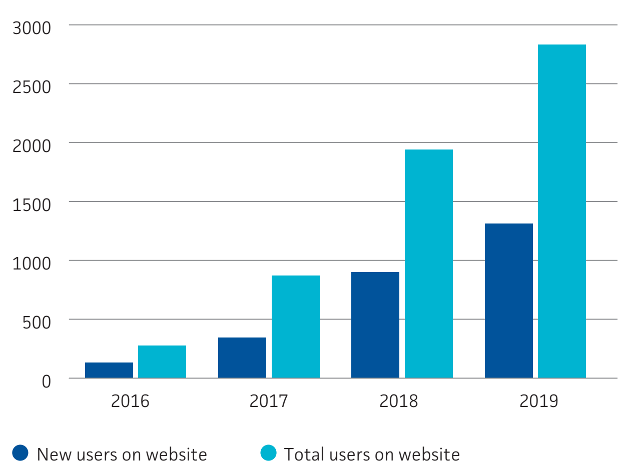
The NCCS webpage provides information about the Centre, its research and other activities like events and conferences. In 2019, the website was updated with a more modern, user-friendly design.



The top five countries to visit nccs.no in 2019



Website development since Centre-start



Newsletter

The NCCS newsletter mainly goes out to the Consortium but is also open to external subscribers. In 2019, 19 newsletters were sent out, providing information about NCCS events, research, blogposts, media coverage etc.

- December 19, 2019 NCCS Christmas Greeting 2019
- December 5, 2019 NCCS Newsletter December - Oxidative degradation, Fault and fracture stability, Utilization of waste and ImpreCCS
- October 9, 2019 CO_2 capture plant and CO_2 liquefaction
- September 30, 2019 CO_2 flow and Storage safety - NCCS Newsletter October 2019
- September 17, 2019 NCCS Newsletter September 2019
- July 5, 2019 NCCS Newsletter July - 2019
- July 3, 2019 TCCS-10 – Jubilee with success
- June 14, 2019 TCCS Newsletter #12 - Important information to all participants
- June 13, 2019 TCCS Newsletter #11 - Conference information and videos
- June 3, 2019 TCCS Newsletter #10 - Third presentations of keynote speakers
- May 29, 2019 TCCS Newsletter #9 - Second presentations of keynote speakers
- May 24, 2019 TCCS Newsletter #8 - First presentations of keynote speakers
- May 22, 2019 TCCS Newsletter #7 - Sponsors, keynote speakers and programme
- April 26, 2019 TCCS Newsletter #6 - Program and CCS Award Deadline
- April 3, 2019 TCCS Newsletter #5 - Early bird deadline, sponsor info and new video
- February 15, 2019 TCCS Newsletter #4, 2018 Sponsor prospectus
- February 13, 2019 TCCS Newsletter #3, 2019 - Practical information and hotel accomodation
- February 6, 2019 TCCS Newsletter #2, 2019 - Registration and Submission of abstracts
- January 15, 2019 TCCS Newsletter #1, 2019

Twitter

The NCCS Twitter account (@NCCS_FME) is used to share news about Centre activities, popular science publications like videos, posts on #SINTEFBlog and conference news. The target groups of the account are consortium members, potential partners, researchers, policy makers (domestic and international) and the interested members of the public.

In 2019, NCCS had:

550 followers

129 000 Twitter views

44 tweets

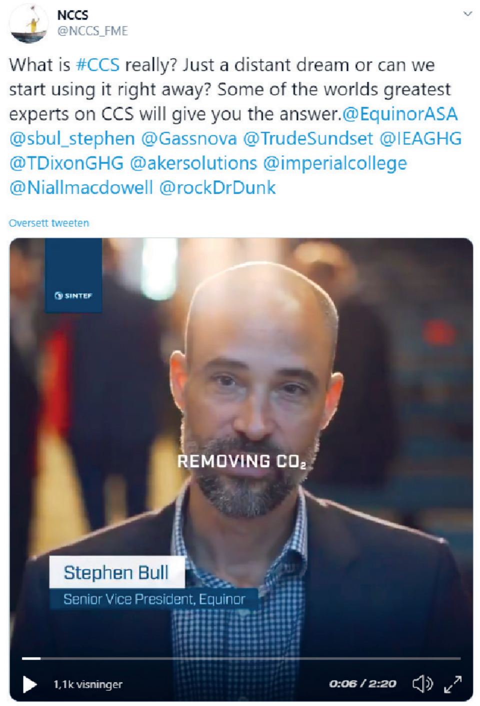
The most popular tweet of 2019 was the "What is CCS" video made after the TCCS-10 conference, where CCS experts shared their thoughts on what CCS is and what needs to be done to realise it. The tweet had:

19 000
views

1 100
video views

301
engagements
(I.e. retweets, likes, etc.)

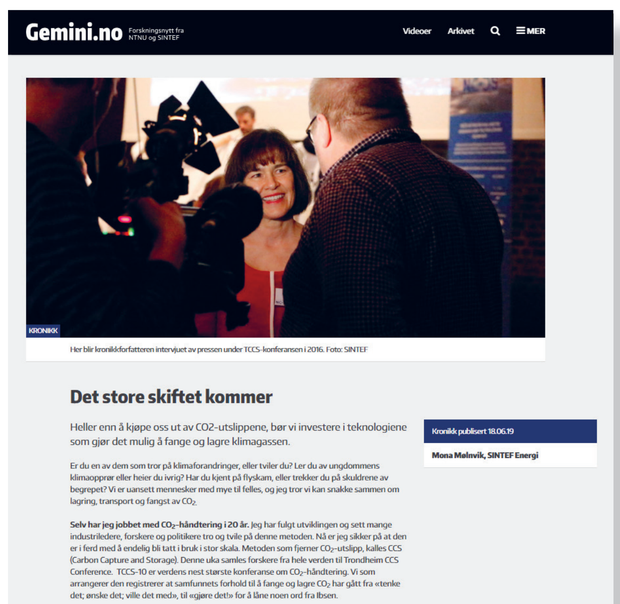
June was the most successful month on social media for NCCS in 2019, with over 21 000 views on Twitter. In comparison, the best month of 2018 had 11 000 views!


NCCS
@NCCS_FME
What is #CCS really? Just a distant dream or can we start using it right away? Some of the worlds greatest experts on CCS will give you the answer.@EquinorASA @sbul_stephen @Gassnova @TrudeSundset @IEAGHG @TDixonGHG @akersolutions @imperialcollege @Niallmacdowell @rockDrDunk
Oversett tweeten

Visibility

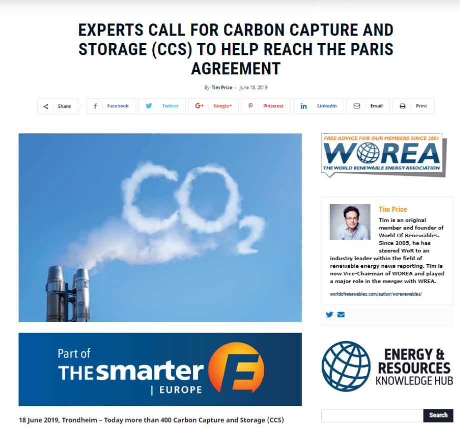
In addition to attending and presenting at important conferences, political meetings etc, NCCS always aims at reaching a wide audience through the media in order to affect both political and public acceptance. Here are five examples of NCCS media visibility in 2019:

#1: Op-ed leading up to TCCS-10
Leading up to the TCCS-10 conference in June, NCCS Director Mona Mølnvik wrote an op-ed: "Det store skiftet kommer" (The Great Shift is Coming). The Op-ed argues that climate actions which seem expensive today, e.g. CCS, are not that expensive after all. What's expensive is pretending nothing is happening and letting climate change run its course. The op-ed was picked up by several Norwegian media houses, including Dagens Næringsliv, Klassekampen and Gemini.


Gemini.no
Det store skiftet kommer
Heller enn å kjøpe oss ut av CO2-utslippene, bør vi investere i teknologiene som gjør det mulig å fange og lagre klimagassen.
Kronikk publisert 18.06.19
Mona Mølnvik, SINTEF Energi


MENINGER
KRONIKK &DEBATT
Heller enn å kjøpe oss ut av CO_2-utslipp, bør vi omfavne det som er framtida – utslippsfrie løsninger.
Det store skiftet kommer
Iskald juni
Skivebom, Utheim!
Det er ikke dyrt med klimatiltak i dag.

#2: TCCS-10 in international news
In the weeks leading up to the TCCS-10 conference a press release was sent out. Here are two examples of international media which picked it up:


EXPERTS CALL FOR CARBON CAPTURE AND STORAGE (CCS) TO HELP REACH THE PARIS AGREEMENT


NEWS
Experts Call For Carbon Capture And Storage (CCS) To Help Reach The Paris Agreement
More than 400 Carbon Capture and Storage (CCS) experts and global leaders in the CCS field gathered in Trondheim at the opening of the 10th bi-annual Trondheim CCS Conference (TCCS), a leading scientific CCS conference.

#3: Article about CCS in Norwegian SciTech News
CCS Experts from SINTEF and NTNT were interviewed in the article "All you need to know about CCS" (Dette må du vite om fangst og lagring av CO_2), published at gemini.no (Norwegian SciTech News) in October. The article goes in depth on what CCS is and how it works. From NCCS the following were interviewed: Strategic Advisory Group Leader, Nils Røkke, Centre Director Mona Mølnvik, Task 7 Leader Svend Tollak Munkejord, Task 11 Leader Alv-Arne Grimstad and Task 12 Leader Jon Peder Eliasson


Gemini.no Forskningsnytt fra NTNU og SINTEF
Videoer Arkivet MER

Norge har verdens største testanlegg for CO_2-fangstteknologi. Dette ligger på Mongstad (bildet). I likhet med andre teknologier som er dyre i starten, har CO2-fangst blitt mer effektiv og dermed rimeligere. Foto: MariusLTU/iStock

Dette må du vite om fangst og lagring av CO2

Hvorfor er det så mye snakk om å lagre CO_2 i undergrunnen? Koster det ikke mer enn det smaker? Her forteller forskere hvorfor vi er helt avhengige av teknologien som kan fange og lagre CO_2. Og ja, det kan gjøres på en trygg måte.

Av Christina Benjaminsen
Publisert 10.10.19

Hva er egentlig CCS?

CCS er en forkortelse for det engelske begrepet Carbon Capture and Storage. På norsk kaller vi det karbonfangst og -lagring. Karbonet som omtales er klimagassen CO_2, altså kullsyre, som vi slipper ut når vi for eksempel brenner olje, kull og gass, når vi produserer sement, og i andre industrielle produkter.

CCS er altså en teknologi som kan fange, transportere og lagre CO_2-en trygt under jordskorpa. Derfor har mange begynt å omtale CCS som karbon-retur, fordi planen er å lagre CO_2-en tilbake i undergrunnen der karbonet kom fra, for eksempel i gamle og stabile oljereservoarer

#4: Article on the cost reduction of CCS
Forskning.no published an article based on the NCCS journal article "Profiting from CCS innovations: A study to measure potential value creation from CCS research and development ". The article documents how CCS-research over the last two decades has ensured vast cost reduction in the CCS value chain. NCCS researches Grethe Tangen and Sigmund Størseth (both authors of the journal article) were interviewed by forskning.no.


Forskere og industri utvikler kunnskap, metoder og teknologi for å gjøre karbon-fangst og lagring til en gjennomførbar løsning. (Foto: Thor Nielsen)

Stadig billigere å fange CO2

Mange års forskningsinnsats har redusert kostnaden for fullskala fangst og lagring av CO2 betydelig, viser ny studie.

Mona Sprenger
SKRIBENT FOR GEMINI.NO
SINTEF

PUBLISERT Fredag 05. april 2019 - 04:30

#5: Vår Energi joins NCCS
In 2019 a new industry partner, Vår Energi, joined NCCS. *"This partnership complements Vår Energi's research and development portfolio. The company is committed to reduce the emissions of greenhouse gases through CCS technology development"*, says Oddvar Ims, R&D Manager in Vår Energi. Vår Energi joining NCCS was picked up by both Norwegian and international media.


Vår Energi investerer i forskning på karbonfangst- og lagring

enerwe

PUBLISERT Fredag 15. februar 2019 - 20:58


HITECVISION
The Serial Entrepreneurs

ABOUT US RESPONSIBILITY PORTFOLIO TEAM NEWS CONTACT

VÅR ENERGI INVESTS IN CARBON CAPTURE AND STORAGE RESEARCH

Vår Energi has entered into a partnership with the Norwegian Carbon Capture & Storage Research Centre (NCCS) to enable fast track CCS technology development and deployment. The agreement has a total value of 30 million NOK over a six-year period and is part of an industry-driven and science-based innovation effort.

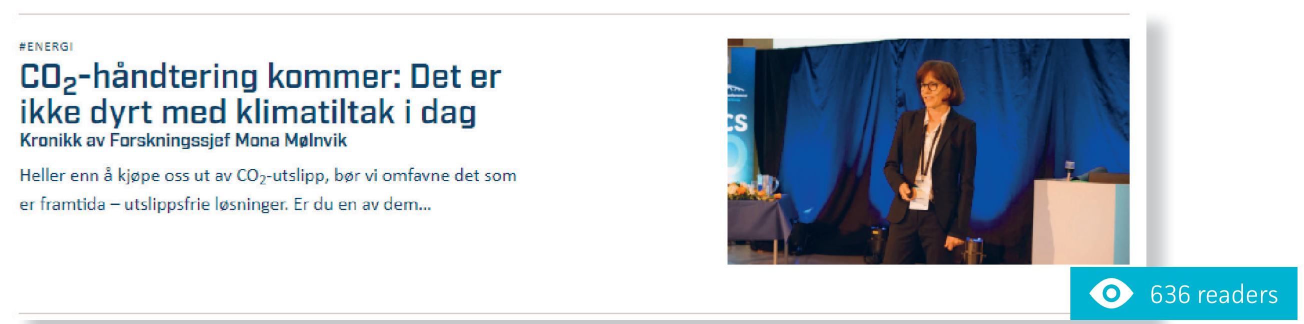
"*This partnership complements Vår Energi's research and development portfolio. The company is committed to reduce the emissions of greenhouse gases through CCS technology development*", says Oddvar Ims, R&D Manager in Vår Energi.

Vår Energi will contribute by investing 5 million NOK every year for a period of six years. The joint industry project commenced in 2017 and will continue until 2025. NCCS' main objective is to become a world-leading CCS Centre by enabling fast-track CCS technology development and deployment by addressing major barriers in industry projects.

Blog

NCCS published 17 blogposts on the SINTEF Blog in 2019. Most blog posts are spin-offs from scientific publications that go in-depth on NCCS science and research. The blog posts are written in more of a popular science style than the publications they are based on. They are aimed at other researchers (both within and outside the field), policy makers and people working in areas related to CCS.

The top three blogpost of 2019 were:


#ENERGI

CO_2-håndtering kommer: Det er ikke dyrt med klimatiltak i dag

Kronikk av Forskningssjef Mona Mølnvik

Heller enn å kjøpe oss ut av CO_2-utslipp, bør vi omfavne det som er framtida – utslippsfrie løsninger. Er du en av dem...

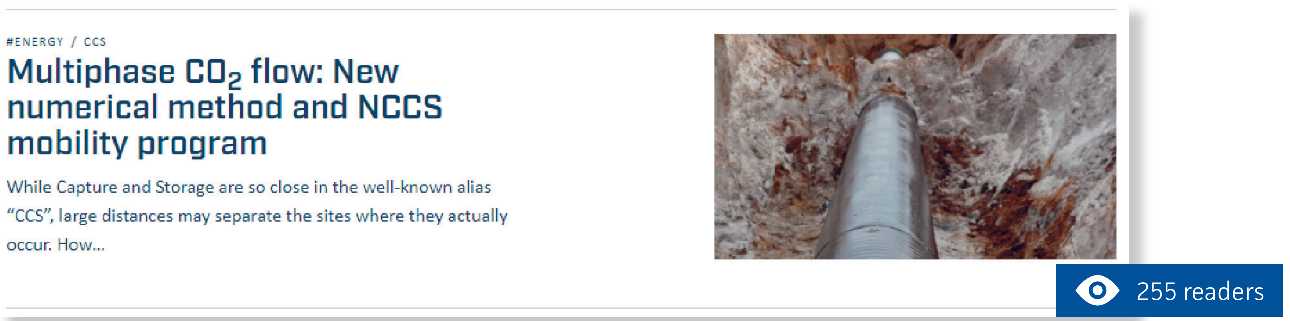
636 readers


#ENERGY / CCS

Better understanding of CO_2 liquefaction (Towards identifying optimal transport conditions for ship-based CCS)

Ship-based transport of CO_2 is an attractive technology for early deployment of CCS. It has several advantages like cost-effectiveness for long distances and...

337 readers


#ENERGY / CCS

Multiphase CO_2 flow: New numerical method and NCCS mobility program

While Capture and Storage are so close in the well-known alias "CCS", large distances may separate the sites where they actually occur. How...

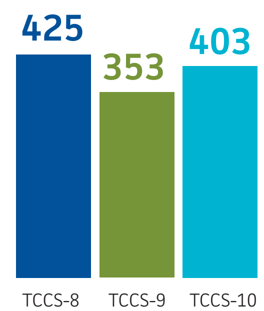
255 readers

TCCS-10

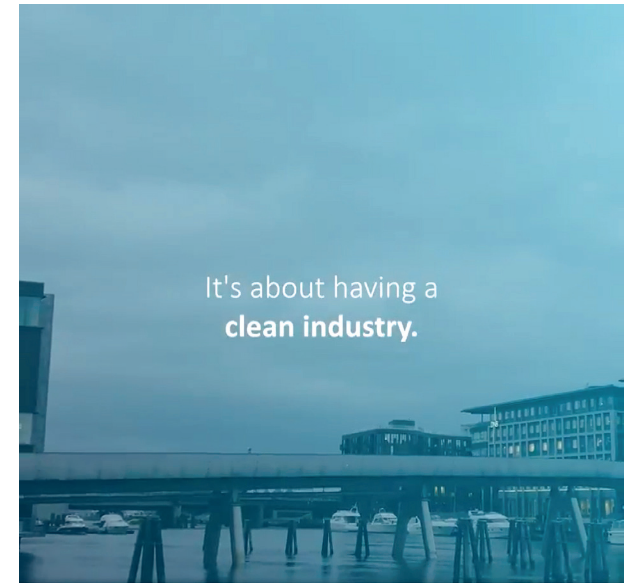
In June 2019, NCCS hosted the 10th Trondheim CCS Conference (TCCS-10) on behalf of SINTEF and NTNU. TCCS is a bi-annual, globally leading scientific CCS conference, gathering over 400 research scientists and other experts from around the world in Trondheim to share and discuss the latest CCS research. This is the arena where Trondheim cements itself as the CCS capital of the world, spearheaded by NCCS.

The Conference is also an important political arena. In 2019 TCCS-10 was opened by the Minister of Petroleum and Energy. After the opening the Minister sat through several keynotes, including our own Centre Director Mona Mølnvik, who spoke of the importance of CCS to reach climate targets, and the progress of (N) CCS research. In an interview after the opening session the Minister stated that CCS is an imperative tool to maintain living standards, settlement patterns and an industry which produces the goods and services we are dependent on.

Great effort was put into marketing TCCS-10. Instead of aiming the marketing effort far and wide, media relevant to CCS, social media, newsletters, direct contact with potential attendees and the Organising Committee's CCS network was utilized to promote the conference to the most relevant audiences. Promotion of the Conference also started earlier than before. As a result of great organising, scientific quality and targeted marketing, NCCS was able to turn declining attendance numbers.



Number of attendees at the three last TCCS conferences.



Snippet from the main promotional video, aimed at international research and academia.

Examples from the marketing of TCCS-10

From a video with SINTEF President and CEO Alexandra Bech Gjørv. She promotes the conference to Norwegian industry and policy makers.

Most keynote speakers recorded a short video of themselves where they promoted their keynote. Here are three examples. From the bottom: Kjell Børge Freiberg, Minister of Petroleum and Energy, Katherine Romanak, Research Scientist, University of Texas, Trude Sundset, CEO, Gassnova.

APPENDIX 1

NCCS PUBLICATIONS REGISTERED IN CRISTIN

Peer reviewed Journal publications

From: 2019 *To:* 2019 *sub-category:* Academic article *sub-category:* Academic literature review *sub-category:* Short communication *All publishing channels*

1. **Aditya, Konduri; Gruber, Andrea; Xu, Chao; Lu, Tianfeng F.; Krisman, Alex; Bothien, Mirko R.; Chen, Jacqueline H.**
Direct numerical simulation of flame stabilization assisted by autoignition in a reheat gas turbine combustor. *Proceedings of the Combustion Institute* 2019 ;Volume 37.(2) p. 2635-2642. ENERGISINT
2. **Almenningen, Stian; Betlem, Peter; Hussain, Arif; Roy, Srikumar; Senger, Kim; Ersland, Geir.**
Demonstrating the potential of CO_2 hydrate self-sealing in Svalbard, Arctic Norway. *International Journal of Greenhouse Gas Control* 2019 ;Volume 89. p. 1-8. UiB UNIS
3. **Anantharaman, Rahul; Roussanaly, Simon; Ditaranto, Mario.**
Feasibility of Selective Exhaust Gas Recycle Process for Membrane-based CO_2 Capture from Natural Gas Combined Cycles – Showstoppers and Alternative Process Configurations. *SSRN* 2019. ENERGISINT
4. **Deng, Han; Roussanaly, Simon; Skaugen, Geir.**
Techno-economic analyses of CO_2 liquefaction: Impact of product pressure and impurities. *International journal of refrigeration* 2019 ;Volume 103. p. 301-315 ENERGISINT
5. **Dupuy, Bastien; Torres Caceres, Veronica Alejandra; Romdhane, Mohamed Anouar; Ghaderi, Amir.**
Norwegian large-scale CO_2 storage project (Smeaheia): baseline geophysical models. *SSRN* 2019. SINTEF
6. **Grimstvedt, Andreas Magnar; Wiig, Merete; Einbu, Aslak; Vevelstad, Solrun Johanne.**
Multi-component analysis of monethanolamine solvent samples by FTIR. *International Journal of Greenhouse Gas Control* 2019 ;Volume 83. p. 293-307. SINTEF
7. **Hennings, Peter H.; Lund Snee, Jens-Erik; Osmond, Johnathon Lee; DeShon, Heather R.; Dommisse, Robin; Horne, Elizabeth; Lemons, Casee; Zoback, Mark D.**
Injection-induced seismicity and fault-slip potential in the Fort Worth Basin, Texas. *Bulletin of The Seismological Society of America (BSSA)* 2019 ;Volume 109.(5) p. 1615-1634.UiO
8. **Jiang, Yuanjie; del Alamo Serrano, Gonzalo; Gruber, Andrea; Bothien, Mirko R.; Seshadri, Kalyanasundaram; Williams, Forman Arthur.**
A skeletal mechanism for prediction of ignition delay times and laminar premixed flame velocities of hydrogen-methane mixtures under gas turbine conditions. *International journal of hydrogen energy* 2019; Volume 44.(33) p. 18573-18585. ENERGISINT
9. **Li, Zuoan; Polfus, Jonathan Marc; Xing, Wen; Denonville, Christelle; Fontaine, Marie-Laure; Bredesen, Rune.**
Factors Limiting the Apparent Hydrogen Flux in Asymmetric Tubular Cercer Membranes Based on La27W3.5Mo1.5O55.5−δ and La0.87Sr0.13CrO3−δ. *Membranes* 2019 ;Volume 9.(126). SINTEF
10. **Lubrano-Lavadera, Paul Louis Francois; Senger, Kim; Lecomte, Isabelle; Mulrooney, Mark Joseph; Kühn, Daniela.**
Seismic modelling of metre-scale normal faults at a reservoir-cap rock interface in Central Spitsbergen, Svalbard: implications for CO_2 storage. *Norwegian Journal of Geology* 2019 ;Volume 99.(2) p. 329-347. NORSAR UiB UiO UNIS
11. **Løvseth, Sigurd Weidemann; Westman, Snorre Foss; Austegard, Anders; Stang, Hans Georg Jacob.**
Need and Measurements of Accurate Thermodynamic Data for CCS. *SSRN* 2019. ENERGISINT
12. **Mølnvik, Mona J.; Brunsvold, Amy; Tangen, Grethe; Henriksen, Partow Pakdel; Munkejord, Svend Tollak; Jakobsen, Jana Poplsteinova.**
The Norwegian CCS Research Centre: Industry-Driven Innovation for Fast-Track Ccs Deployment. *SSRN* 2019. ENERGISINT NTNU SINTEF
13. **Ohm, Sverre Ekrene; Larsen, Leif; Olaussen, Snorre; Senger, Kim; Birchall, Thomas; Demchuk, Thomas; Hodson, Andrew; Johansen, Ingar; Titlestad, Geir Ove; Karlsen, Dag Arild; Braathen, Alvar.**
Discovery of shale gas in organic-rich Jurassic successions, Adventdalen, Central Spitsbergen, Norway. *Norwegian Journal of Geology* 2019 ;Volume 99.(2) p. 349-376. IFE UiO UIS UNIS
14. **Olaussen, Snorre; Senger, Kim; Braathen, Alvar; Grundvåg, Sten-Andreas; Mørk, Atle.**
You learn as long as you drill; research synthesis from the Longyearbyen CO_2 Laboratory, Svalbard, Norway. *Norwegian Journal of Geology* 2019 ;Volume 99.(2) p. 157-188. NTNU UiO UiT UNIS
15. **Osmond, Johnathon Lee; Meckel, Timothy A.**
Enhancing trap and fault seal analyses by integrating observations from HR3D seismic data with well logs and conventional 3D seismic data, Texas inner shelf. *Geological Society Special Publication* 2019 p. - UiO
16. **Ottøy, Sindre; Neumann, Tobias; Stang, Hans Georg Jacob; Jakobsen, Jana Poplsteinova; Austegard, Anders; Løvseth, Sigurd Weidemann.**
Thermodynamics of the carbon dioxide plus nitrogen plus methane (CO_2 + N_2 + CH_4) system: Measurements of vapor-liquid equilibrium data at temperatures from 223 to 298 K and verification of EOS-CG-2019 equation of st ate. *Fluid Phase Equilibria* 2019 ;Volume 509. ENERGISINT NTNU
17. **Ringrose, Philip; Meckel, T A.**
Maturing global CO_2 storage resources on offshore continental margins to achieve 2DS emissions reductions. *Scientific Reports* 2019 ;Volume 9.(1) p. 1-10. NTNU
18. **Romdhane, Mohamed Anouar; Eliasson, Peder.**
Optimised Geophysical Survey Design for CO_2 Monitoring – A Synthetic Study. *SSRN* 2019. SINTEF
19. **Roussanaly, Simon.**
Calculating CO_2 avoidance costs of Carbon Capture and Storage from industry. *Carbon Management* 2019; Volume 10.(1) p. 105-112. ENERGISINT
20. **Sazinas, Rokas; Sunding, Martin Fleissner; Thøgersen, Annett; Sakaguchi, Isao; Norby, Truls Eivind; Grande, Tor; Polfus, Jonathan M.**
Surface reactivity and cation non-stoichiometry in BaZr1-xYxO3-δ (x=0-0.2) exposed to CO_2 at elevated temperature. *Journal of Materials Chemistry A* 2019; Volume 7.(8) p. 3848-3856. NTNU SINTEF UiO
21. **Størset, Sigmund Østtveit; Tangen, Grethe; Berstad, David Olsson; Eliasson, Peder; Hoff, Karl Anders; Langørgen, Øyvind; Munkejord, Svend Tollak; Roussanaly, Simon; Torsæter, Malin.**
Profiting from CCS innovations: A study to measure potential value creation from CCS research and development. *International Journal of Greenhouse Gas Control* 2019; Volume 83. p. 208-215. ENERGISINT SINTEF

Presentations

From: 2019 *To:* 2019 *Main category:* Conference lecture and academic presentation *All publishing channels*

1. **Anantharaman, Rahul.**
Benchmarking MEA performance – concentration, scale and practicalities. NCCS Consortium Days 2019; 2019-10-22 - 2019-10-23. ENERGISINT
2. **Anell, Ingrid Margareta.**
NCCS – Education, mobility, student engagement and visions for the future. NCCS Consortium Days; 2019-10-22 - 2019-10-23. UiO
3. **Anell, Ingrid Margareta; Backer, Dag; Sundal, Anja; Torvanger, Asbjørn; Meisingset, Egil; Rørvik, Kari-Lise; Øye, Olav.**
Feasibility of CO_2 storage as a climate mitigation measure in Norway. Outside the BoCCS - CCS Seminar series; 2019-03-13 - 2019-03-13. UiO CICERO
4. **Anell, Ingrid Margareta; Banet, Catherine; Weber, Viktor; Vold, Sofie Fogstad; Riseng, Cathrine; Seglem, Heidi; Svendsen Skriung, Camilla.**
The role of law in CCS deployment – Regulatory incentives to enable carbon capture and storage (CCS) in Norway. Outside the BoCCS - CCS Seminar series; 2019-11-14 - 2019-11-14. UiO
5. **Austegard, Anders; Deng, Han; Hammer, Morten; Løvseth, Sigurd Weidemann; Munkejord, Svend Tollak; Stang, Hans Georg Jacob.**
A new experimental facility for decompression of CO_2 and CO_2-rich mixtures. 10th Trondheim CCS Conference, TCCS-10; 2019-06-17 - 2019-06-19. ENERGISINT
6. **Banet, Catherine.**
"Public support to carbon capture and storage (CCS) under EU state aid rules.". Climate emergency: the role of law in CCS deployment: Regulatory incentives to enable carbon capture and storage (CCS) in Norway and Europe.; 2019-11-14 - 2019-11-14. UiO
7. **Banet, Catherine.**
Public support to carbon capture and storage (CCS) under EU state aid rules. NCCS Consortium Days; 2019-10-22 - 2019-10-23. UiO

8. **Banet, Catherine.**
Rør- og sjøtransport av CO_2. Juridiske hindringer for å gjennomføre fullskala CO_2-håndtering. Teknas CO_2 konferanse 2019; 2019-01-17 - 2019-01-17. UiO
9. **Barrabino, Albert; Bergmo, Per Eirik Strand; Grimstad, Alv-Arne; Holt, Torleif.**
Mobility control of CO_2 during aquifer storage. 10th Trondheim Conference on Carbon Capture, Transport and Storage (TCCS-10); 2019-06-17 - 2019-06-19. SINTEF
10. **Berntsen, Andreas Nicolas.**
Ensuring CO_2 well integrity. CLIMIT Summit; 2019-02-26 - 2019-02-27. SINTEF
11. **Bjerkevedt, Vegard; Roussanaly, Simon; Tomasgard, Asgeir.**
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2. **Aarlien, Rune.**
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3. **Aarlien, Rune.**
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11. **Mølnvik, Mona J.**
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These publications have non-Norwegian authors, only.

1. B. Re; R. Abgrall, Transient multi-phase flows at Low-Mach-A novel simulation tool for weakly compressible flows of CO_2-rich mixtures (POSTER), TCCS-10, June 17-19, Trondheim, Norway
2. R. V. Figueiredo, D. Bakker, A. Huizinga, J. Monteiro, E. Goetheer, De-oxygenation as countermeasure for the reduction of oxidative degradation of CO_2 capture solvents, TCCS-10, June 17-19, Trondheim, Norway
3. J. Monteiro, P. Gravesteijn, E. Goetheer, Short-cut oxidative degradation test for CO_2 capture solvents, TCCS-10, June 17-19, Trondheim, Norway
4. Lorena F.S.Souza, Stefan Herrig, Roland Span, J.P. Martin Trusler, Experimental density and an improved Helmholtz-energy-explicit mixture model for (CO_2 + CO), Applied Energy, Volume 251, 2019, 113398

APPENDIX 2

Accounting Statement 2019

Costs	NOK
Personnel and indirect costs	20 715 921
Purchased R&D services	38 985 330
Other operational costs	4 044 649
Total costs	**63 745 900**

Funding	NOK
Own funding	4 589 075
Other public funding	19 229 834
Other private funding	13 182 723
International funding	1 745 268
RCN funding	24 999 000
Total funding	**63 745 900**

APPENDIX 3
PERSONNEL

Master degrees

Name	Sex	Topic	Task	Univ.	Year
Isabella Stellwag	F	Testing of oxygen removal technology	2	TNO	2018
Avinash S.R. Subramanian	M	Reducing energy consumption in the production of hydrogen from natural gas	6		
Niklas Hunka	M	Description of accurate viscosity setup for CCS	8		
Hong Yan	F	Rock physics inversion for CO_2 characterization at Sleipner	12	NTNU	2017
Veronica Alejandra Torres Caceres	F	Seismic wave attenuation in partially saturated sandstone and AVO analysis for carbon dioxide quantification at Sleipner	12	NTNU	2017
Heidi Sydnes Egeland	F	CCS under the EU ETS: Legal consequences of the CO_2 shipping option	1	UiO	2019
Laura Sole Montana	F	Oxidative degradation of water lean solvents	2	NTNU	2019
Tonje Laukvik and Marianne Laukvik	F	Quantification of nitrogen loss in oxidative degradation experimants using total nitrogen analyser	2	NTNU	2019
Sindre Ottøy	M	Investigation of CO_2-N_2-CH4 mixture: VLE measurements and analysis of Helmholtz energy-based EOS	8	NTNU	2019
Sharon Harris	F	The uplift and subsidence history of the Cenozoic depositional sedimentary successions in Smeaheia, a proposed CO_2 injection and storage site, and influence on overburden properties	9	UiO	2019
Jens Kolnes	M	Reconstruction of the uplift and subsidence history of Smeaheia, a proposed CO_2 injection and storage site	9	UiO	2019
Elias Heimdal Leon	M	Correlation between Quaternary pockmarks and underlying geology within the Smeaheia CO_2 storage area	9	UiO	2019
Ådne Bjerkeli	M	A detailed structural analysis of the Øygarden Fault and footwall bock. Implications for CCS in the Smeaheia prospect	9	UiO	2019
Karoline Helen Løvlie	F	A structural analysis of the upper Agardhfjellet Formation	9	UiO/UNIS	2020
Lise Nakken	F	A caprock integrity evaluation of the lower Agarhdfjellet Formation	9	UiO/UNIS	2020
Isa Adi Subagjo	M	Joint rock physics inversion of seismic and electromagnetic data for CO_2 monitoring at Sleipner	12	NTNU	2018
Henderson Gabriel Pinto Guerrero	M	2-D and 2.5-D Multi-scale Full-Waveform Inversion in frequency domain for high-resolution P-wave velocity (Vp) and quality factor (Q) models at Sleipner field.	12	NTNU	2018
Robin David Kifle	M	Study on seismic data sensitivity on pressure-saturation discrimination	12	UiO	2019
Scott William Christopher Bunting	M	Value of information analysis in the context of leakage detection in CO_2 storage	12	NTNU	2019

Our mobility

Name	Nationality	Sex	Stay at	Topic of work	Period	Duration (mos)	Task
Vanja Buvik	Norway	F	TNO	PhD experiments	October, 2019	1	2

Key Researchers

Name	Institution	Main research area	Task
Simon Roussanaly	SINTEF Energy Research	CO_2 value chain and techno-economic modelling	1
Geir Skaugen	SINTEF Energy Research	Thermodynamic and process optimisation	1
Han Deng	SINTEF Energy Research	Thermodynamic and process optimisation	1,7,8
Asgeir Tomasgard	NTNU	Industrial economics	1
Ozgu Turgut	NTNU	Industrial economics	1
Vegard Bjerketvedt	NTNU	Industrial economics	1
Catherine Banet	UiO	Legal	1
Catherine Banet	UiO	Legal	1
Viktor Weber	UiO	Legal	1
Johannes Dalen Giske	UiO	Legal	1
Heidi Sydnes Egeland	UiO	Legal	1
Solrun Johanne Vevelstad	SINTEF Industry	Post combustion CO_2 capture	2
Andreas Grimstvedt	SINTEF Industry	Post combustion CO_2 capture	2
Merete Wiig	SINTEF Industry	Post combustion CO_2 capture	2
Inna Kim	SINTEF Industry	Post combustion CO_2 capture	2
Hanna Knuutila	NTNU	Post combustion CO_2 capture	2
Peter van Os	TNO	Post combustion CO_2 capture	2
Earl Goeether	TNO	Post combustion CO_2 capture	2
Juliana Garcia Moretz-Sohn Monteiro	TNO	Post combustion CO_2 capture	2
Roberta Veronez Figueiredo	TNO	Post combustion CO_2 capture	2
Jonathan Polfus	SINTEF Industry	Ceramic membranes	3
Einar Vøllestad	SINTEF Industry	Ceramic membranes	3
Harald Malerød-Fjeld	CoorsTek Membrane Sciences	Ceramic Membranes	3
David Berstad	SINTEF Energy Research	CO_2 liquefaction	4
Stian Trædal	SINTEF Energy Research	CO_2 liquefaction	4
Jacob Stang	SINTEF Energy Research	CO_2 liquefaction	4,8
Andrea Gruber	SINTEF	Numerical modelling of reactive flows	5
Gonzalo del Alamo	SINTEF	Chemical kinetics modelling	5
James R Dawson	NTNU	Experimental combustion dynamics	5
Nicholas Worth	NTNU	Experimental combustion dynamics	5
Rahul Anantharaman	SINTEF Energy Research	CO_2 capture process integration and design	1,6
Chao Fu	SINTEF Energy Research	Process modelling and integration	6
Vidar Skjervold	SINTEF Energy Research	Process modelling	6
Kristin Jordal	SINTEF Energy Research	CO_2 capture process integration and design	6
Svend Tollak Munkejord	SINTEF Energy Research	CO_2 transport	7
Stéphane Dumoulin	SINTEF Industry	CO_2 transport	7
Gaute Gruben	SINTEF Industry	CO_2 transport	7
Morten Hammer	SINTEF Energy Research	CO_2 transport	7,8
Sigurd Weidemann Løvseth	SINTEF Energy Research	CO_2 Thermodynamics / Fiscal metering	8
Anders Austegard	SINTEF Energy Research	CO_2 thermodyn. / fiscal metering / transport prop	7,8
Caroline Einen	SINTEF Energy Research	CO_2 thermodyn. / fiscal metering / transport prop	8
Lars Lars Hov Odsæter	SINTEF Energy Research	CO_2 transport properties	8
Francesco Finotti	SINTEF Energy Research	CO_2 fiscal metering	8
Roland Span	Ruhr Universität-Bochum	CO_2 thermodynamics	8
Jana Popsteinova Jakobsen	NTNU	CO_2 thermodynamics / transport properties	8
Eric May	UWA	CO_2 transport properties	8
Arash Arami Niya	UWA	CO_2 transport properties	8
Edward Jukes	Krohne Ltd	CO_2 fiscal metering	8
Elin Skurtveit	NGI/UiO	Structural geology	9
Alvar Braathen	UiO	Structural geology	9
Jung Chan Choi	NGI	Geomechanics	9
Jan Inge Faleide	UiO	Geophysics	9
Ingrid Anell	UiO	Geology	9
Ivar Midtkandal	UiO	Sedimentology	9
Kim Senger	UNIS	Structural geology	9
Pierre Cerasi	SINTEF Industry	Geomechanics, leakage de-risking	9, 10
Malin Torsæter	SINTEF Industry	Well integrity, leakage de-risking	10
Jelena Todorovic	SINTEF Industry	Well integrity, injectivity impairment	10
Torbjørn Vrålstad	SINTEF Industry	Well integrity, injectivity impairment	10
Kamila Gawel	SINTEF Industry	Well integrity, leakage de-risking	10
Xiyang Xie	SINTEF Industry	Geomechanics, leakage de-risking	9, 10
Laura Edvardsen	SINTEF Industry	Geomechanics, leakage de-risking	10
Nicolaine Agofack	SINTEF Industry	Geomechanics, leakage de-risking	10

Name	Institution	Main research area	Task
Nils Opedal	SINTEF Industry	Well integrity, leakage de-risking	10
Alv-Arne Grimstad	SINTEF Industry	CO_2 storage	11
Albert Barrabino	SINTEF Industry	CO_2 storage	11
Per Bergmo	SINTEF Industry	CO_2 storage	11
Huaitian Bu	SINTEF Industry	CO_2 storage	11
Torleif Holt	SINTEF Industry	CO_2 storage	11
Monika Pilz	SINTEF Industry	CO_2 storage	11
Juan Yang	SINTEF Industry	CO_2 storage	11
Eirin Langseth	SINTEF Industry	CO_2 storage	11
Christian Simon	SINTEF Industry	CO_2 storage	11
Elyes Ahmed	SINTEF Digital	CO_2 storage	11
Xavier Raynaud	SINTEF Digital	CO_2 storage	11
Øystein Klemetsdal	SINTEF Digital	CO_2 storage	11
Christian Bos	TNO	CO_2 storage	11
Filip Neele	TNO	CO_2 storage	11
Frank Wilschut	TNO	CO_2 storage	11
Peder Eliasson	SINTEF Industry	CO_2 storage	12
Bastien Dupuy	SINTEF Industry	CO_2 storage	12
Anouar Romdhane	SINTEF Industry	CO_2 storage	12
Amir Ghaderi	SINTEF Industry	CO_2 storage	12
Halvor Møll Nilsen	SINTEF Digital	CO_2 storage	12,11
Francesca Watson	SINTEF Digital	CO_2 storage	12
Odd Andersen	SINTEF Digital	CO_2 storage	12
Joonsang Park	NGI	CO_2 storage	12
Guillaume Sauvin	NGI	CO_2 storage	12
Jim White	BGS	CO_2 storage	12
Hayley Vosper	BGS	CO_2 storage	12
Gareth Williams	BGS	CO_2 storage	12
Ola Eiken	Quad Geometrics	CO_2 storage	12
Jan Petter Morten	EMGS	CO_2 storage	12
Astrid Kornberg Bjørke	EMGS	CO_2 storage	12
Sigmund Ø. Størset	SINTEF Energy Research	CO_2 capture and process integration, innovation management	ITT
Grethe Tangen	SINTEF Industry	CO_2 storage	ITT
Jon Magne Johansen	SINTEF Energy Research	Innovation management	ITT

Visiting Researchers

Name	Affiliation	Nationality	Sex	Duration	Topic	Task
Martin Khamphasith	Univ. Of Western Australia	Australia	M	08/2019 - 05/2020	VLE measurements	8

Postdoctoral researchers with financial support from the Centre budget

Name	Nationality	Period	Sex	Topic	Task
Tamara Makuni	UK	08/2017 - 12/2017	F	Experimental investigations into forced and self-excited azimuthal combustion dynamics modes	5
Mark Mulrooney	Irland	09/2017 - 09/2021	M	Structural de-risking of the Smeaheia CO_2 storage prospect	9
Ozgu Turgut	Turkey	11/2017 - 11/2020	F	The role of CCS in decarbinizing the power and industrial sectors in Europe and Norway	1
Viktor Weber	Hungary	09/2018 - 08/2021	M	Legal aspects of transport and storage with a focus on liabilities	1
Jose Aguilar	Mexico	08/2018 - 07/2020	M	Gas turbine combustion instabilities for H_2 (CH_4 blends)	5
Barbara Re	Switzerland	01/2018 - 12/2019	F	Large-scale transient behaviour of CO_2-transport pipelines	7

Postdoctoral researchers working on projects in the Centre with financial support from other sources

Name	Nationality	Period	Sex	Topic	Task	Source
Donghoi Kim	South Korea	07/2019 - 06/2021	M	Modeling of hybrid processes (H_2 production and CO_2 liquefaction)	3	KPN: Mach-2
Emma Michie Haines	UK	02/2020 - 07/2022	F	Structural geology	9	KPN: FRISK

PhD students with financial support from the Centre budget

Name	Nationality	Period	Sex	Topic	Task
Vanja Buvik	Norway	10/2017 - 08/2021	F	Effect of amine structure on solvent stability of CO_2 absorbents	2
Lucas Braakhuis	Netherlands	10/2019 - 10/2022	M	Modelling solvent degradation and reclamation in amine-based post-combustion carbon capture	2
Stefan Herrig	Germany	06/2017 - 07/2018	M	New Helmholtz-energy models for pure fluids and CCS-relevant mixtures	8
Jonathon Osmond	USA	10/2017 - 09/2021	M	3D structural characterization and containment risk analysis of two CO_2 storage prospects in the Smeaheia area of the Northern Horda Platform, Norwegian North Sea	9

Name	Nationality	Period	Sex	Topic	Task
Vegard Bjerketvedt	Norway	10/2017 - 10/2020	M	Optimal design and operation of CCS value chains with focus on the transport system	1
Eirik Æsøy	Norway	03/2018 - 03/2022	M	Experimental investigations into forced and self-excited azimuthal combustion dynamics modes	5
Tobias Neumann	Germany	01/2017 - 12/2021	M	Improved description of minor components relevant for the transport of CO_2-rich mixtures including chemically reacting systems	8
Bahereh Khosravi	Iran	12/2018 - 11/2021	F	Viscosity and density measurements of CO_2 and CO_2-rich mixtures at conditions relevant for CCS	8
Camilla Louise Würtzen	Denmark	09/2018 - 09/2021	F	Tectonostratigraphic analysis of CO_2 storage reservoirs in the Upper Triassic alluvial Lunde Formation in the Smeaheia area, Norwegian North Sea	9
Peter Betlem	Netherlands	03/2019 - 03/2023	M	Geological and geophysical analysis of overburden for CO_2 storage sites	9
Magnus Soldal	Norway	06/2019 - 05/2022	M	Fault geomechanics	9
Marcin Duda	Poland	01/2018 - 12/2020	M	Overburden pore pressure changes due to fluid injection	10
Mohammad Masoudi	Iran	09/2018 - 08/2021	M	Modeling nucleation reactions	10

PhD students working on projects in the Centre with financial support from other sources

Name	Funding	Nationality	Period	Sex	Topic	Task
Mats Rongved	KPN project	Norway	08/2015 - 03/2018	M	Hydraulic fracturing for enhanced geothermal systems	10
Dongchan Kim	International	Korea	08/2019 - 04/2020	M	Working on measurements of thermal conductivity	8

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The Research Council of Norway

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